High Energy Neutrino Astronomy

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1. General Introduction

2. Fundamental Mechanism

   for high energy neutrino production

3. Neutrinos versus Gamma Rays

4. Atmospheric Neutrinos

5. The Gamma Ray sky

6. Astrophysical Neutrinos

7. Outlook

1. General Introduction

- Neutrino sources
- Neutrinos from the “High Energy Universe”
- Neutrino Flavor Oscillations

Astrophysics with four MESSENGERS

- Photons

Essentially all the information
we have on the Universe around us
has been obtained with photons.

The history of Astrophysics is the
EXTENSION of the range of
wavelength available for observations

- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Astrophysics with Four MESSENGERS

- Photons
- Neutrinos

A *New Messenger*
with very different properties
that will allow to
"SEE" the universe
in a profoundly different way

- Cosmic Rays (p, e^-, $\bar{p}, e^+$, ...)
- Gravitational waves

Astrophysics with Four MESSENGERS

- Photons
- Neutrinos

Study the structure and properties of the SOURCES

Study the Neutrino properties (oscillations, decay...)

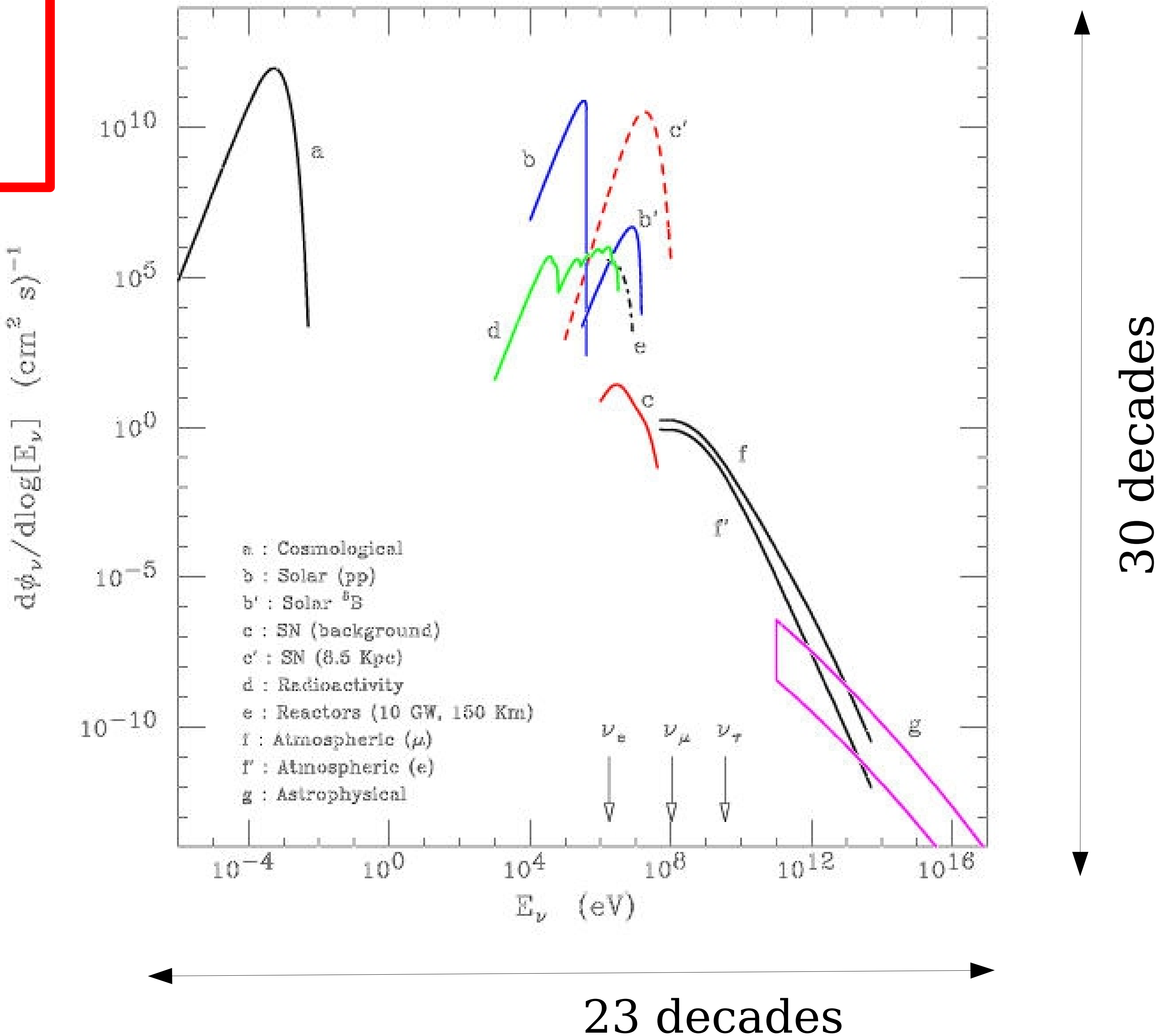
- Cosmic Rays (p, e^-, $\bar{p}, e^+$, ...)
- Gravitational waves

SPACE is
FULL of NEUTRINOS

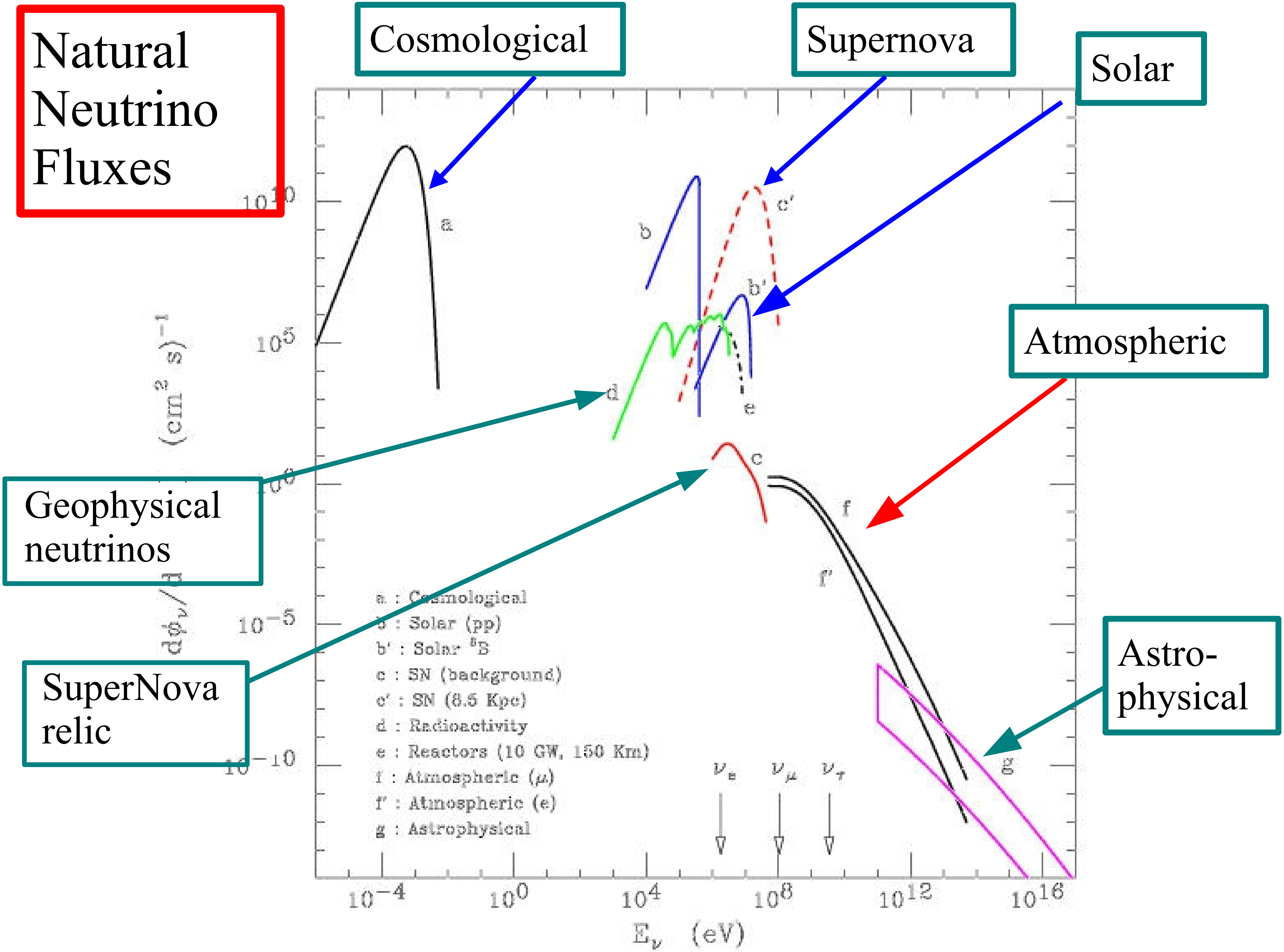
that come from a
variety of sources

in a very broad
interval of energies

Natural Neutrino Fluxes



Natural Neutrino Fluxes



Neutrino Astrophysics is a very diverse field
that extends in a very broad energy range

$E_\nu \simeq 10^{-4}$ eV — Cosmological neutrinos

[......]

"km3 concept" (and extensions)

$E_\nu \simeq 10^{12}$–10^{14} eV — Galactic point sources

$E_\nu \simeq 10^{14}$–10^{16} eV — IceCube signal

$E_\nu \simeq 10^{18}$–10^{20} eV — "GZK neutrinos"

$E_\nu \simeq 10^{23}$ eV — [Speculative neutrinos from supermassive particles decay]

Neutrino Astronomy (or Astrophysics) has just been born at the end of the last Century

TWO (+1) ASTROPHYSICAL OBJECTS have been “seen” in Neutrinos”

The SUN

SuperNova SN1987A

The Earth: Geophysical Neutrinos

SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

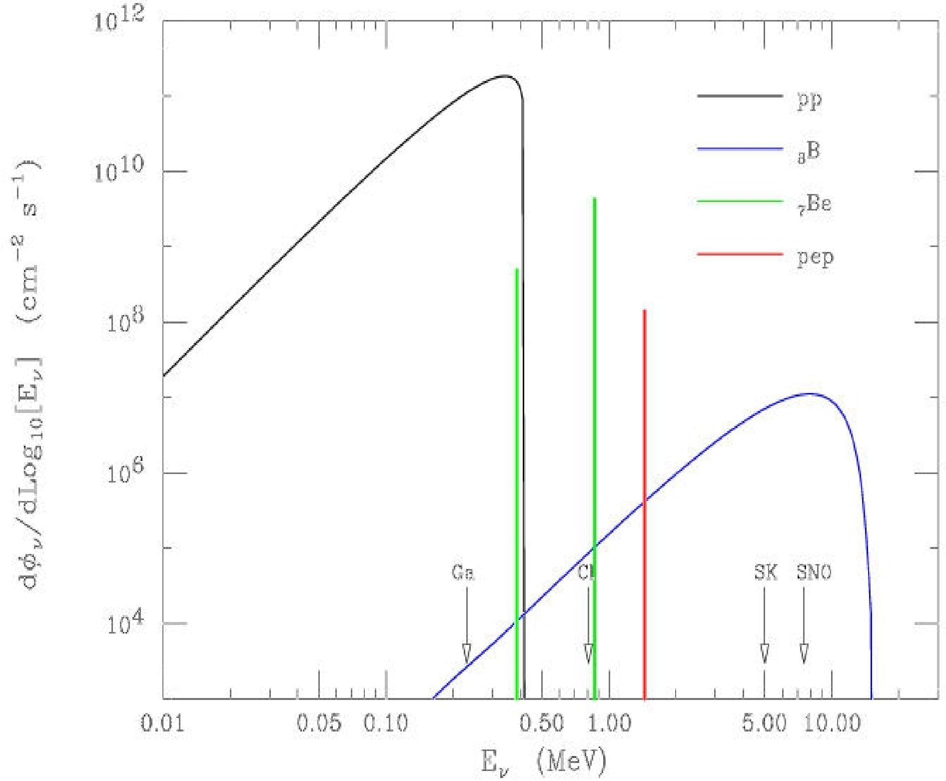
$$4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e$$

Energy Released per each Cycle

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \ \mathrm{MeV}$$

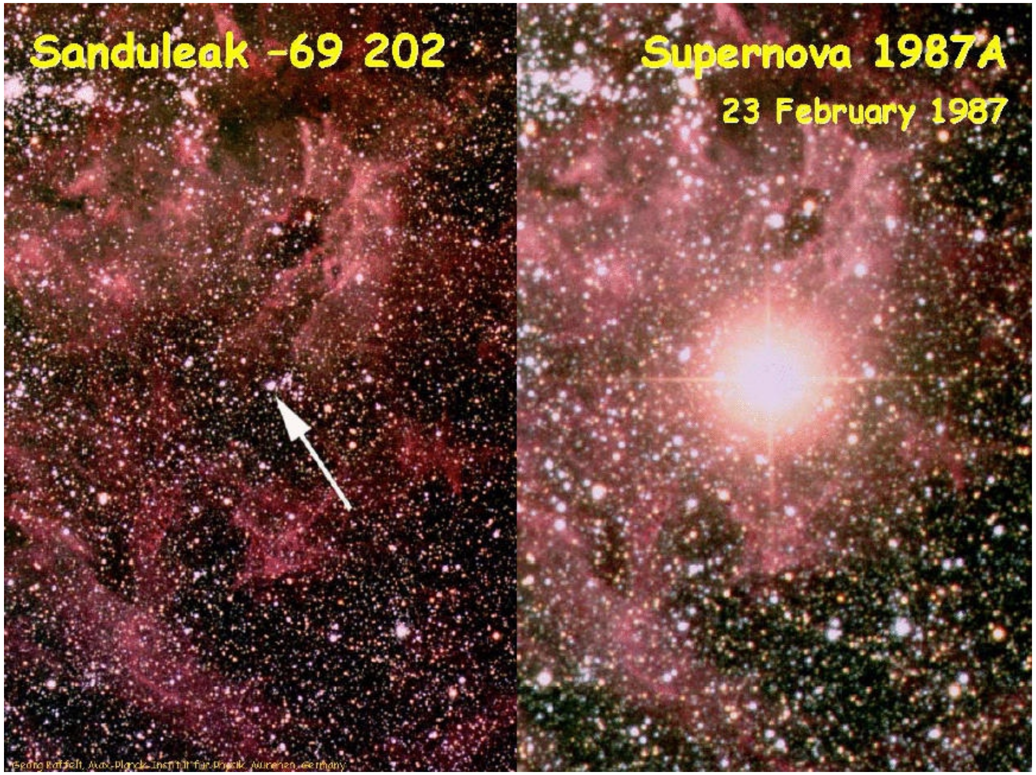
$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \, \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\mathrm{cm}^2 \ \mathrm{s})^{-1}$$



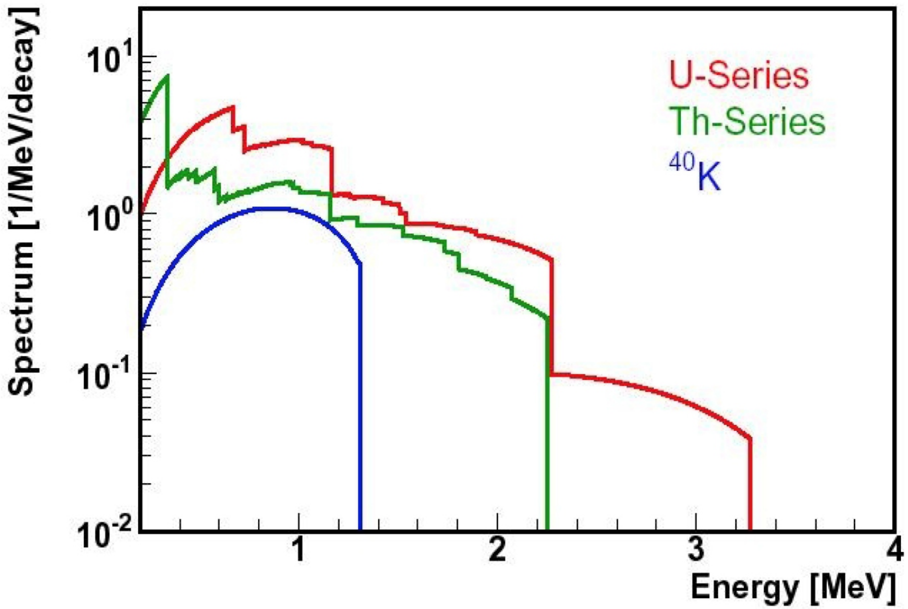
NEUTRINOS from SUPERNOVAE EXPLOSIONS (Gravitational Collapse)

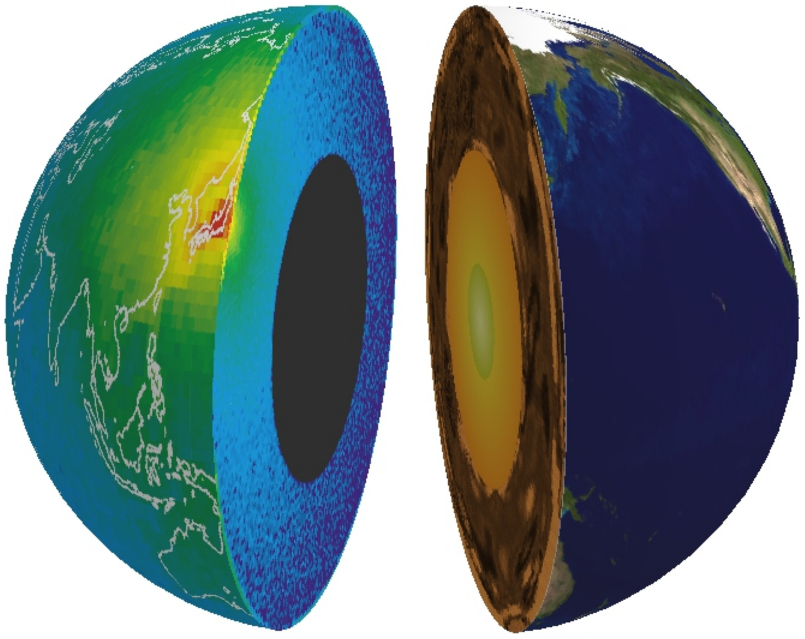
Energy ~ 30 MeV



... 29.6 years ago ....

GEOPHYSICAL NEUTRINOS





$$^{238}\mathrm{U} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e^- + 6\bar{\nu}_e + 51.7\ [\mathrm{MeV}]$$

$$^{232}\mathrm{Th} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e^- + 4\bar{\nu}_e + 42.7\ [\mathrm{MeV}]$$

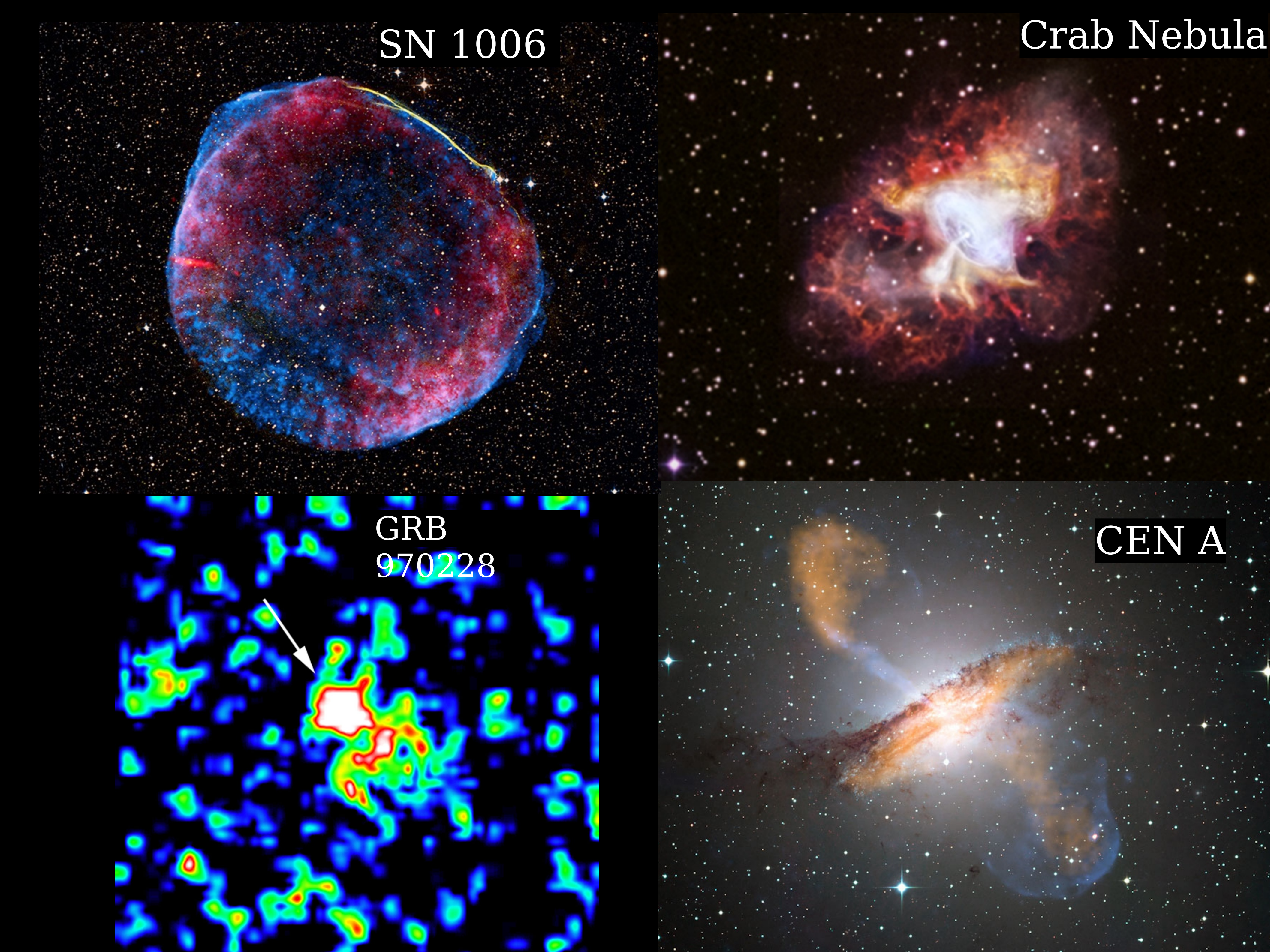
$$^{40}\mathrm{K} \xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ [\mathrm{MeV}]$$

$$^{40}\mathrm{K} + e^- \xrightarrow[10.72\%]{} {}^{40}\mathrm{Ar} + \nu_e + 1.505\ [\mathrm{MeV}]$$

The Cross Section of the Neutrino
is VERY SMALL

PROBLEM :
Detection is Very Difficult
Require Very Large Detectors

OPPORTUNITY:
Neutrinos come from
DEEP INSIDE Astrophysical Objects

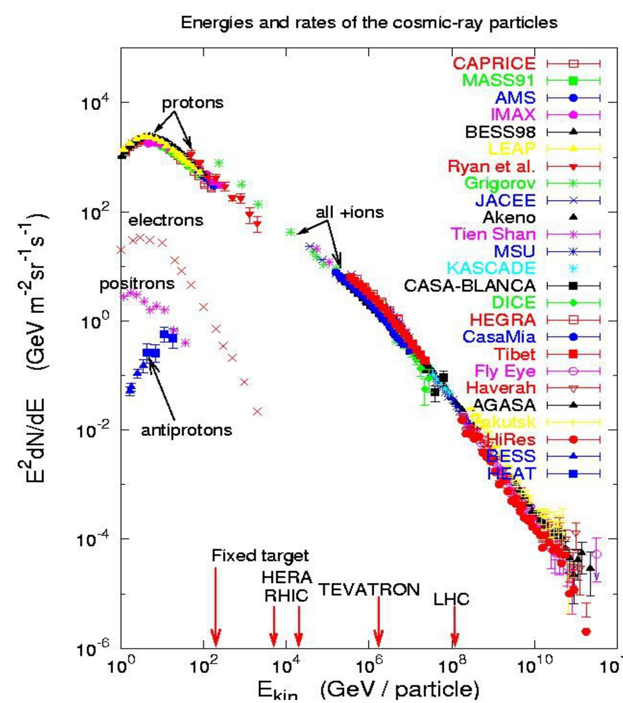

SN 1006
Crab Nebula
GRB
970228
CEN A

COSMIC RAYS

Victor Hess

before the balloon flight of 1912

Discovery of Cosmic Rays
Beginning of
High Energy Astrophysics

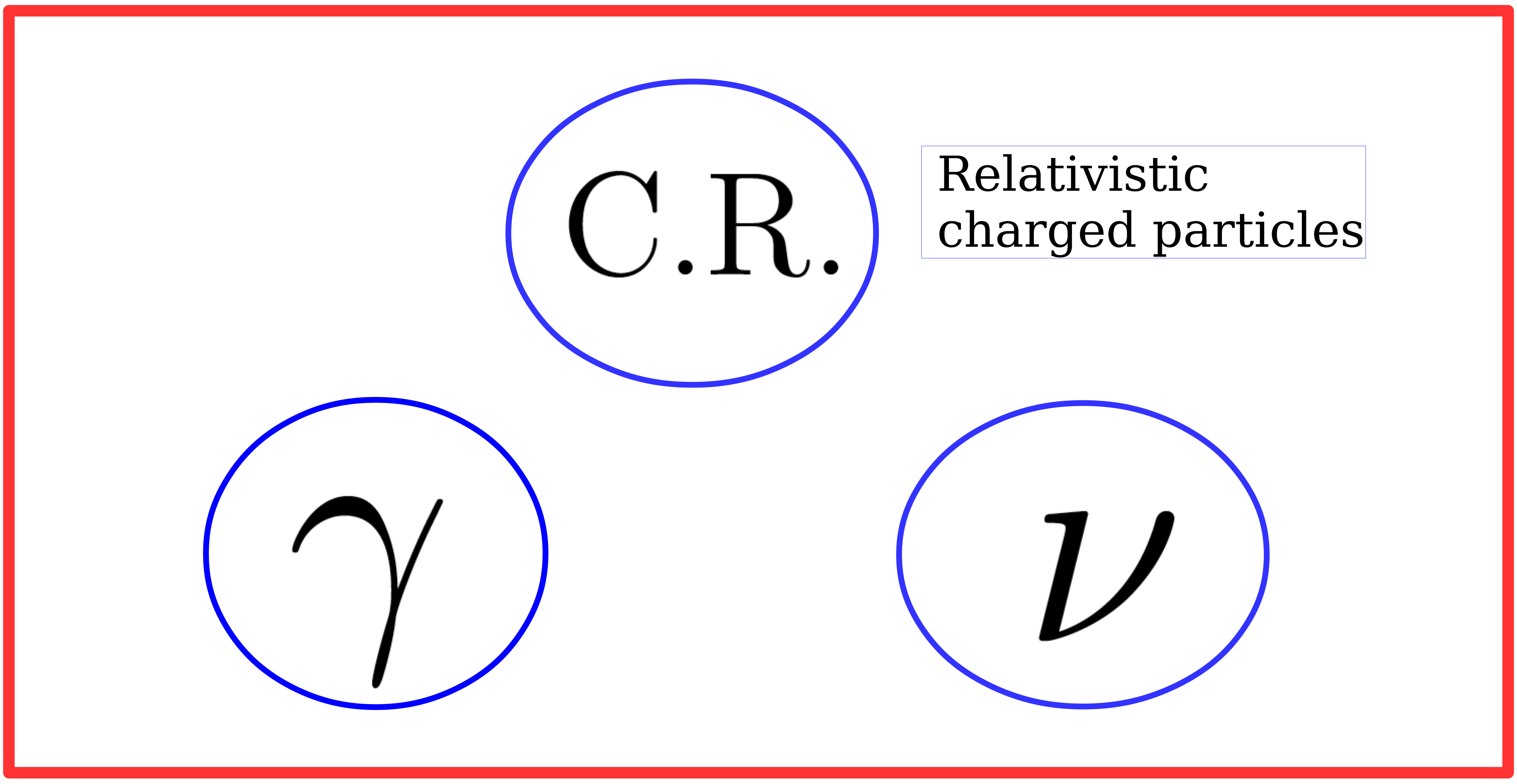


Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

4 Messengers
for the study of the
"High Energy Universe"

Three messengers are “inextricably” tied together
[Cosmic Rays, Gamma Rays, High Energy Neutrinos
can really be considered as three probes that study the
same underlying physical phenomena]



Neutrino Flavor Oscillations:

$$\{\nu_e,\ \nu_\mu,\ \nu_\tau\}$$

Flavor eigenstates

$$\{\nu_1,\ \nu_2,\ \nu_3\}$$

$$\{m_1, m_2, m_3\}$$

Mass eigenstates

(with well defined masses)

$$\boxed{|\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle}$$

Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3 mixing angles

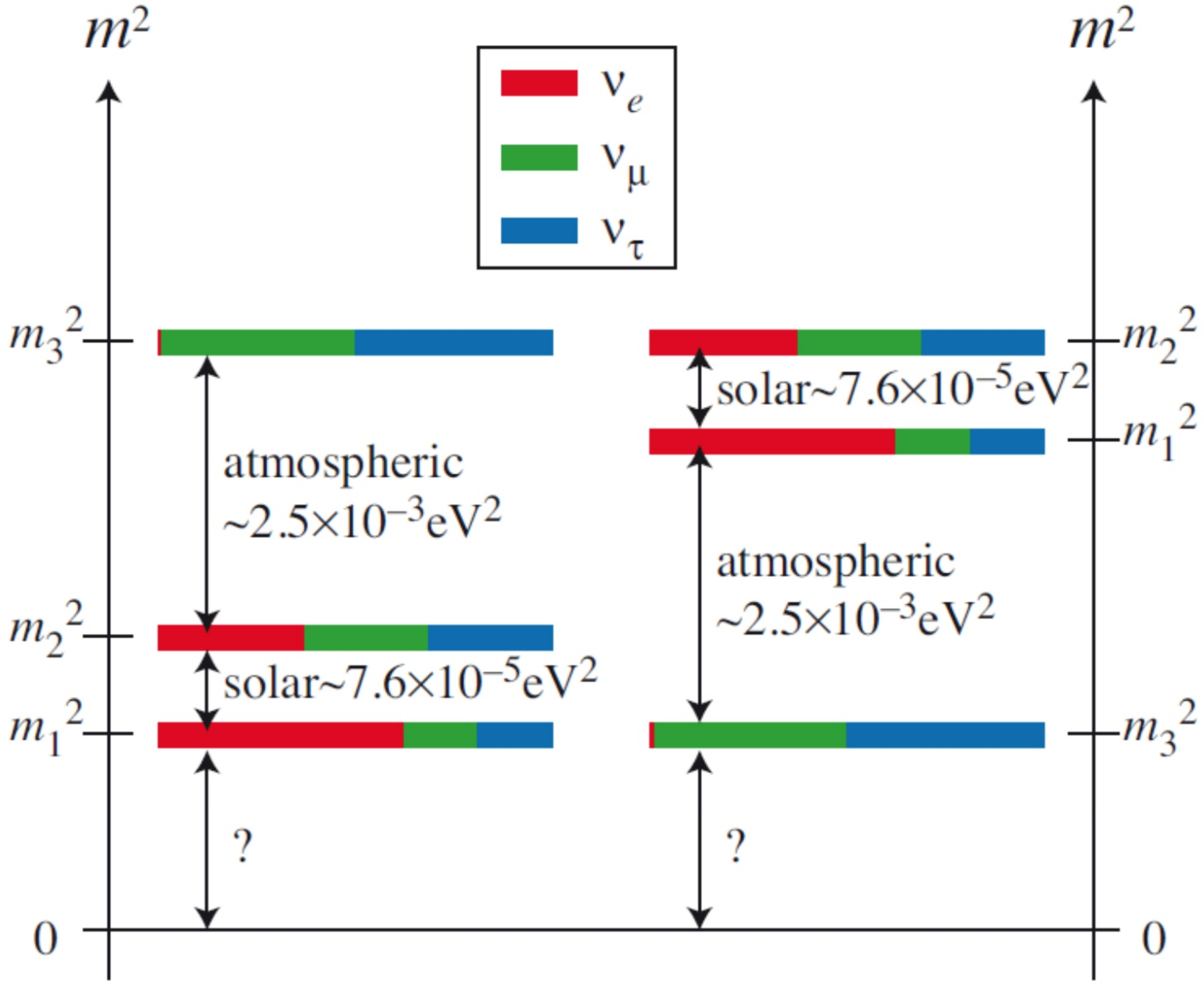
$$(\theta_{12},\ \theta_{13},\ \theta_{23})$$

CP violating phase δ

$$c_{jk} = \cos\theta_{jk}$$

$$s_{jk} = \sin\theta_{jk}$$

Neutrino Mass Hierarchy:



$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) &= \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \, \frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} \; |U_{\beta j}|^2 \; |U_{\alpha j}|^2 \\
&+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E} \right) \\
&+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E} \right)
\end{aligned}
$$

Flavor transition probability

Neutrino created with flavor α
is observed at a distance L
with flavor β

$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) &= \left| \sum_j U_{\beta j} U^*_{\alpha j}\; e^{-i\, m_j^2 \,\frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2 \\
&\xcancel{+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)} \\
&\xcancel{+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)}
\end{aligned}
$$

Flavor transition probability

Neutrinos created in
a volume of linear size

$$X_{\mathrm{source}} \gg E/|\Delta m^2_{jk}|$$

Oscillating terms average to zero

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

$$\simeq \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

$$\theta_{13} \simeq 0$$

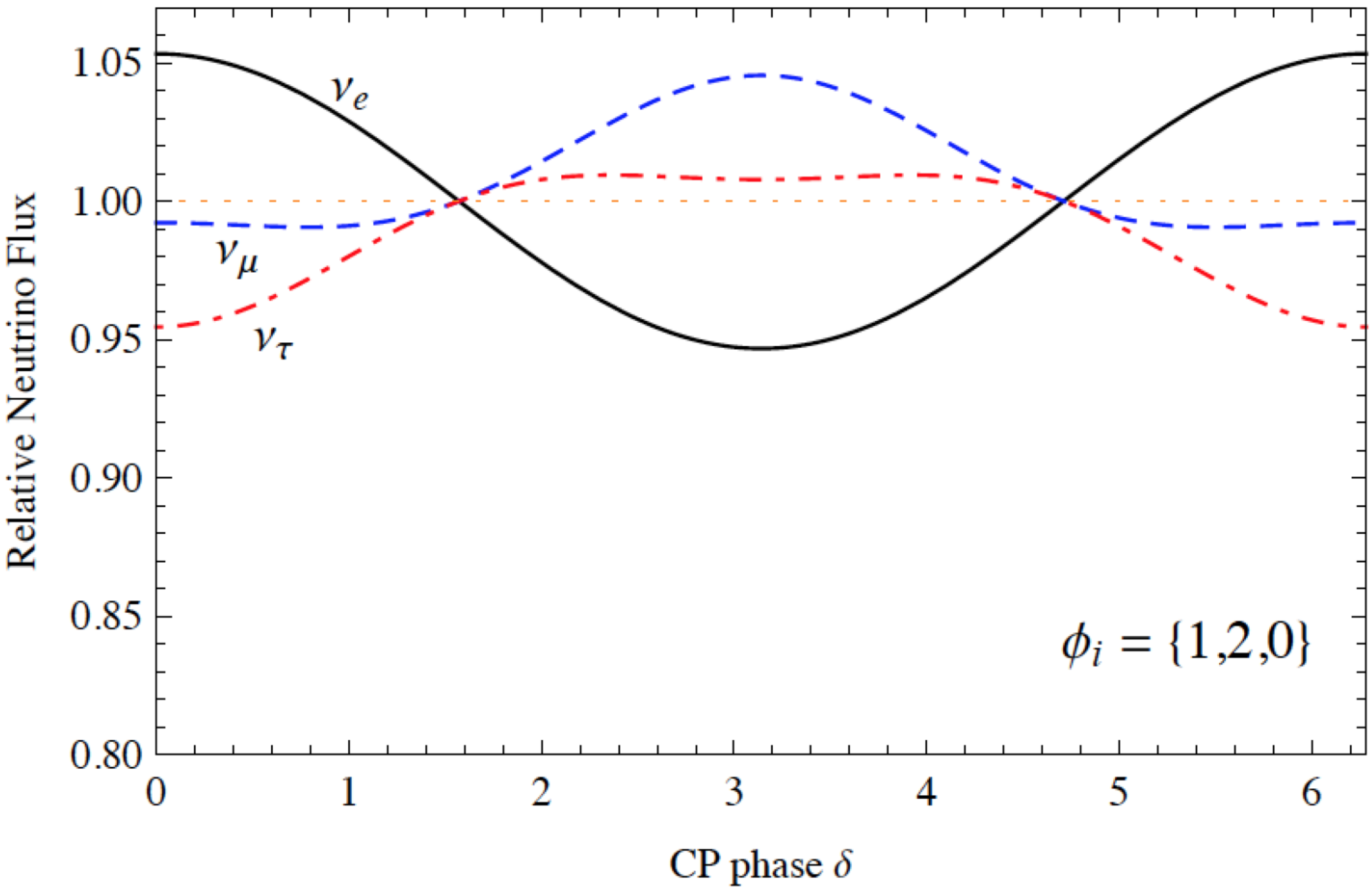
$$\theta_{23} \simeq 45^\circ$$

$$v = \cos^2\theta_{12}\sin^2\theta_{12} \simeq 0.2$$

$$\boxed{\begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}}$$

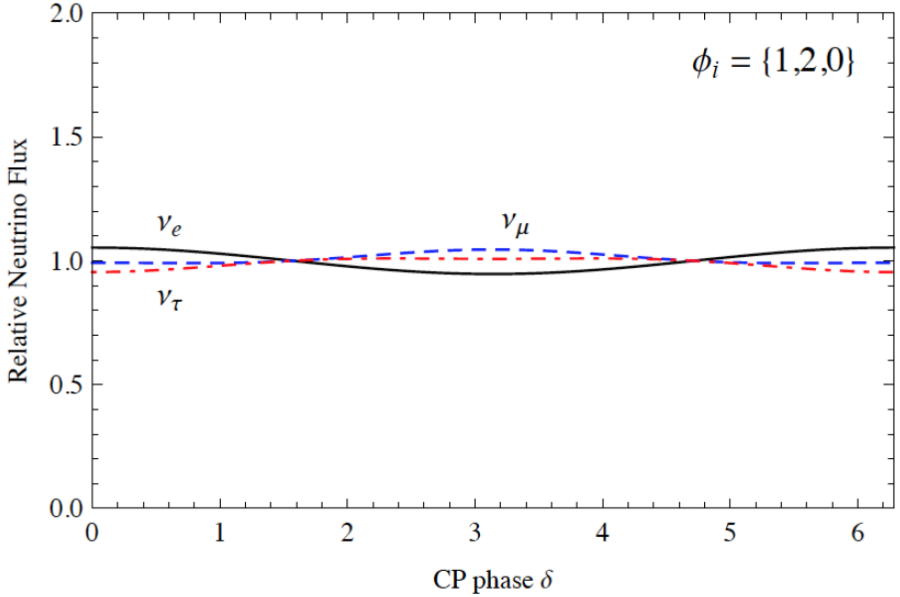
Relative fluxes at the observers
starting from 2 nu_mu and 1 nu_e
(standard mixture for a pion chain-decay origin)

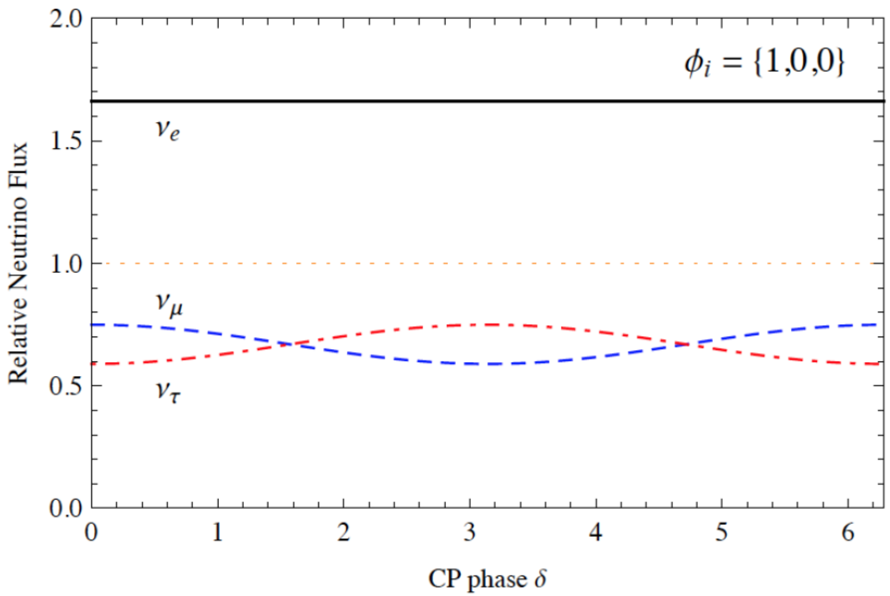
$\theta_{12} \quad \theta_{13} \quad \theta_{23}$ = best fit

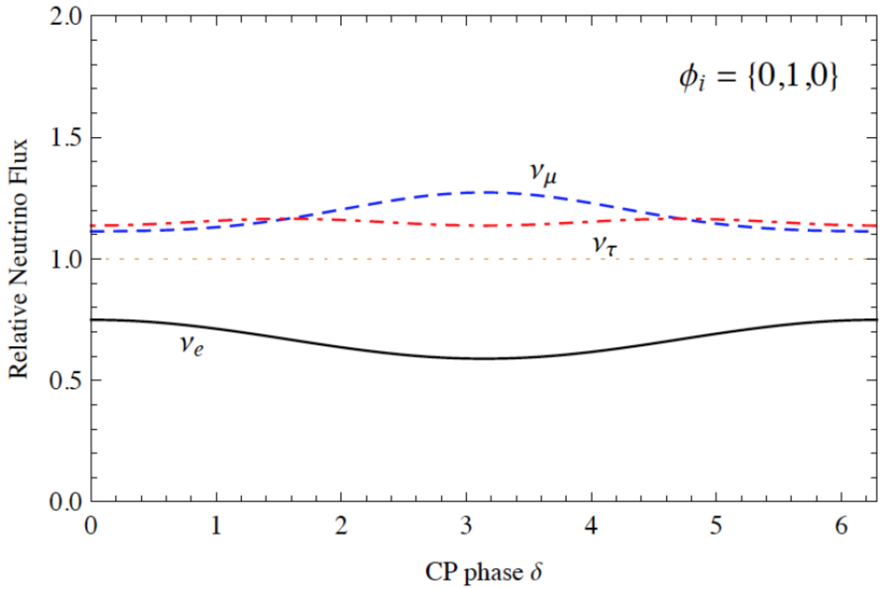


More in general:
For an arbitrary flavor composition emission

Significant presence of tau-neutrinos







Possibility of
"Modifications" of the neutrino flux
during propagation.

Investigate :
Flavor Oscillations (with very long path-lengths)
Decay (with very long lifetimes)
....

Important difficulty:
Properties of the neutrinos at the source
must be sufficiently well understood.

What could one learn about the neutrino properties when astrophysical neutrinos are finally detected ?

Extraordinary Long Baselines

$$L_{\rm galactic} \simeq 3 \times 10^{22}\ {\rm cm}$$

$$L_{\rm extra} \simeq 1.3 \times 10^{28}\ z\ {\rm cm}$$

Oscillations with very small Δm^2

$$\Delta m^2 \sim 10^{-18}\ {\rm eV}^2$$

Example:
[Pseudo-Dirac neutrinos
mass doublets with tiny
mass splitting]

Neutrino Decay (9 orders of magnitude improvement)

Neutrino cross sections at very high energy

2. Fundamental Mechanism

for high energy neutrino production

- Hadronic interactions
- Weak decays
- "pp" versus "$p\gamma$"

Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic "

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

$$\pi^+ \to \mu^+ \; \nu_\mu$$

$$\hookrightarrow e^+ \; \nu_e \; \overline{\nu}_\mu$$

"Leptonic "

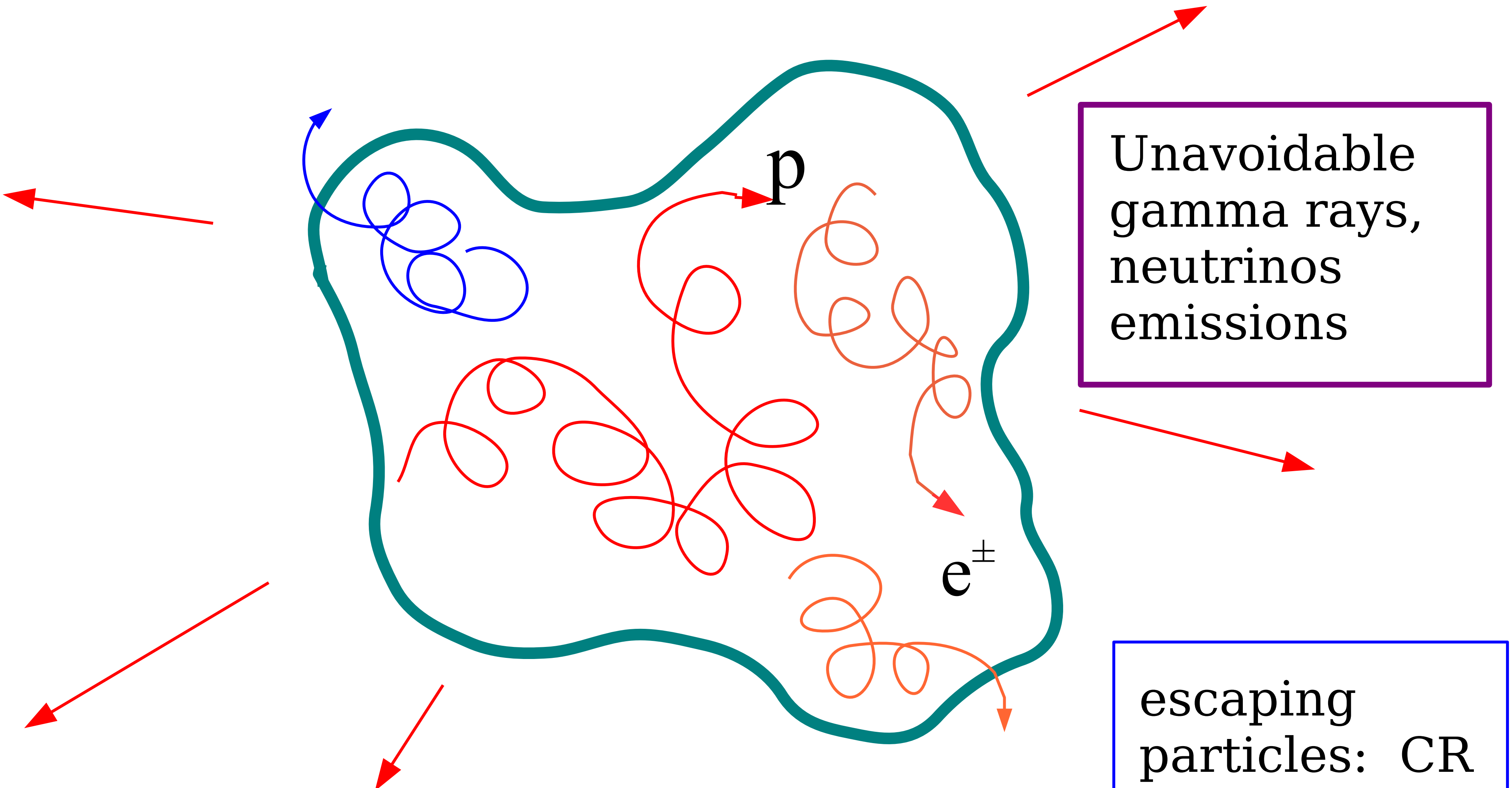
$$e^\pm \; \gamma_{\rm soft} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\rm syn}$$

High Energy Astrophysical Source:

Astrophysical object (or “event”)
that produces (and for some time contains)
relativistic particles



Neutrino Emission by proton-proton interactions

via production and decay of charged pions

$$p + p \rightarrow \pi^+ + \pi^- + \ldots$$

$$\pi^+ \rightarrow \mu^+ \quad \nu_\mu$$

$$\hookrightarrow \quad e^+ \quad \nu_e \quad \overline{\nu}_\mu$$

Smaller contributions from the decay of Kaons $K^\pm$ K_L
+Charmed particles

Photon Emission by Proton interaction

via production and decay of neutral pions

$$p + p \to \pi^\circ + \ldots$$

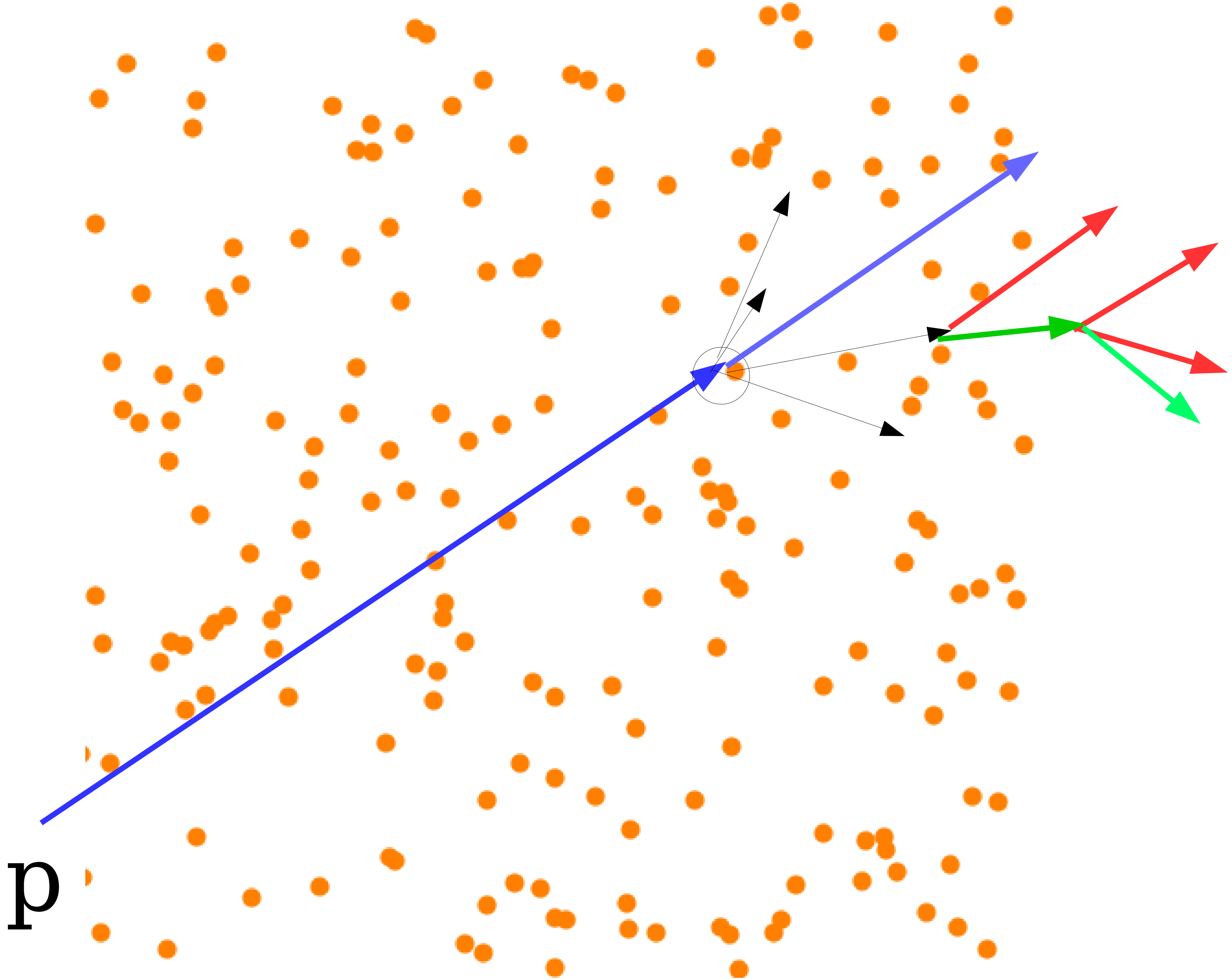
$$\pi^\circ \to \gamma\gamma$$

Smaller contributions from decay of other particles

$$\eta \to \gamma + \ldots$$

$$\eta' \to \gamma + \ldots$$

$[u\overline{u}]$ $[d\overline{d}]$ $[s\overline{s}]$


p

Hadronic mechanism:
(emission of photons by proton interaction).

$$N_p(E) \simeq K\ E^{-\alpha}$$

Relativistic protons
Population in the source.

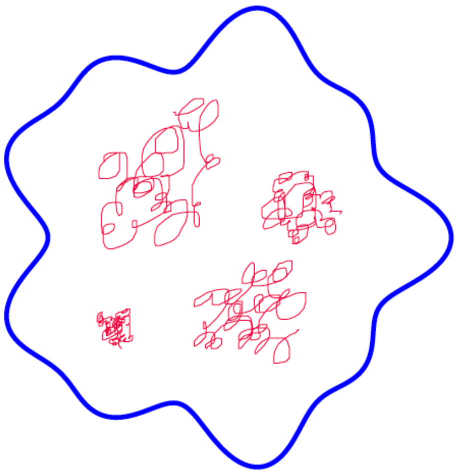
expect (in most cases)
a power law spectrum

A proton in the source has a probability of interacting
in a time dt :

$$dP_{\rm int}(E_p) = \boxed{\sigma_{pp}(E_p)}\, n_p\, \beta c\, dt$$

proton-proton
inelastic cross section

Gas density in the target



$$\phi_\nu(E_\nu) = \frac{1}{4\,\pi\,d^2}\;\dot{N}_\nu(E_\nu)$$

Flux observed at the Earth

$$\dot{N}_\nu(E_\nu) = \int_{E_\gamma}^{\infty} dE_p\; N_e(E_p)\;\frac{dP_{\rm int}(E_p)}{dt}\;\boxed{\frac{dN_{p\to\nu}(E_\nu, E_p)}{dE_\nu}}$$

Number of neutrinos of energy E_ν
produced in an interaction
of a proton of energy E_p

$$\dot{N}_\nu(E_\nu) = \int_{E_\gamma}^{\infty} dE_p \; N_e(E_p) \; \frac{dP_{\rm int}(E_p)}{dt} \; \boxed{\frac{dN_{p\to\nu}(E_\nu, E_p)}{dE_\nu}}$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; N_e(E_p) \; \frac{dP_{\rm int}(E_p)}{dt} \; \boxed{\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}}$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; \boxed{N_e(E_p)} \; \boxed{\frac{dP_{\rm int}(E_p)}{dt}} \; \boxed{\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}}$$

$$\boxed{N_p(E) \simeq K \; E^{-\alpha}}$$

$$\boxed{\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma} \simeq \frac{1}{E_\gamma} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)}$$

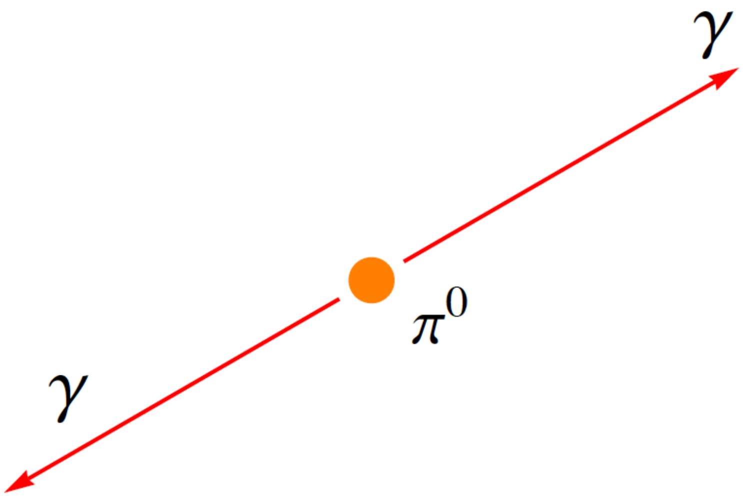
$$\boxed{\frac{dP_{\rm int}(E_p)}{dt} = \sigma_{pp}(E_p)\, n_p \; \beta c}$$

"Scaling function"

Convolution of the probability of creating a neutral pion of a certain energy + probability that the pion decay into a photon of energy E_γ

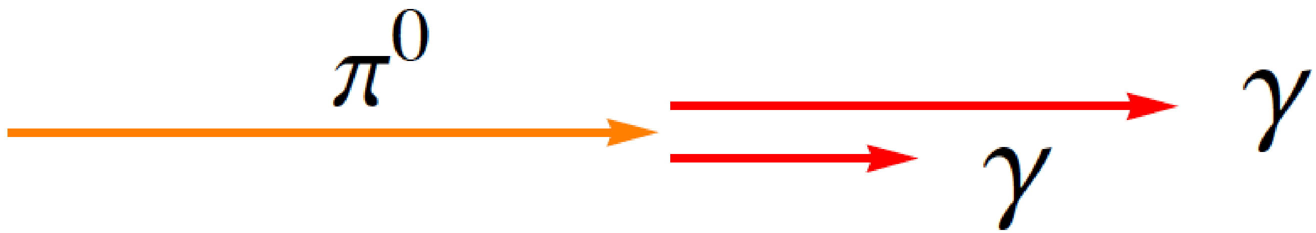
Pion decay into photons:

$$\boxed{\pi^\circ \rightarrow \gamma\gamma}$$



Rest Frame $$E_\gamma = \frac{m_\pi}{2}$$

Photons are emitted isotropically
and monochromatically with a fixed energy.



Frame where the pion is moving

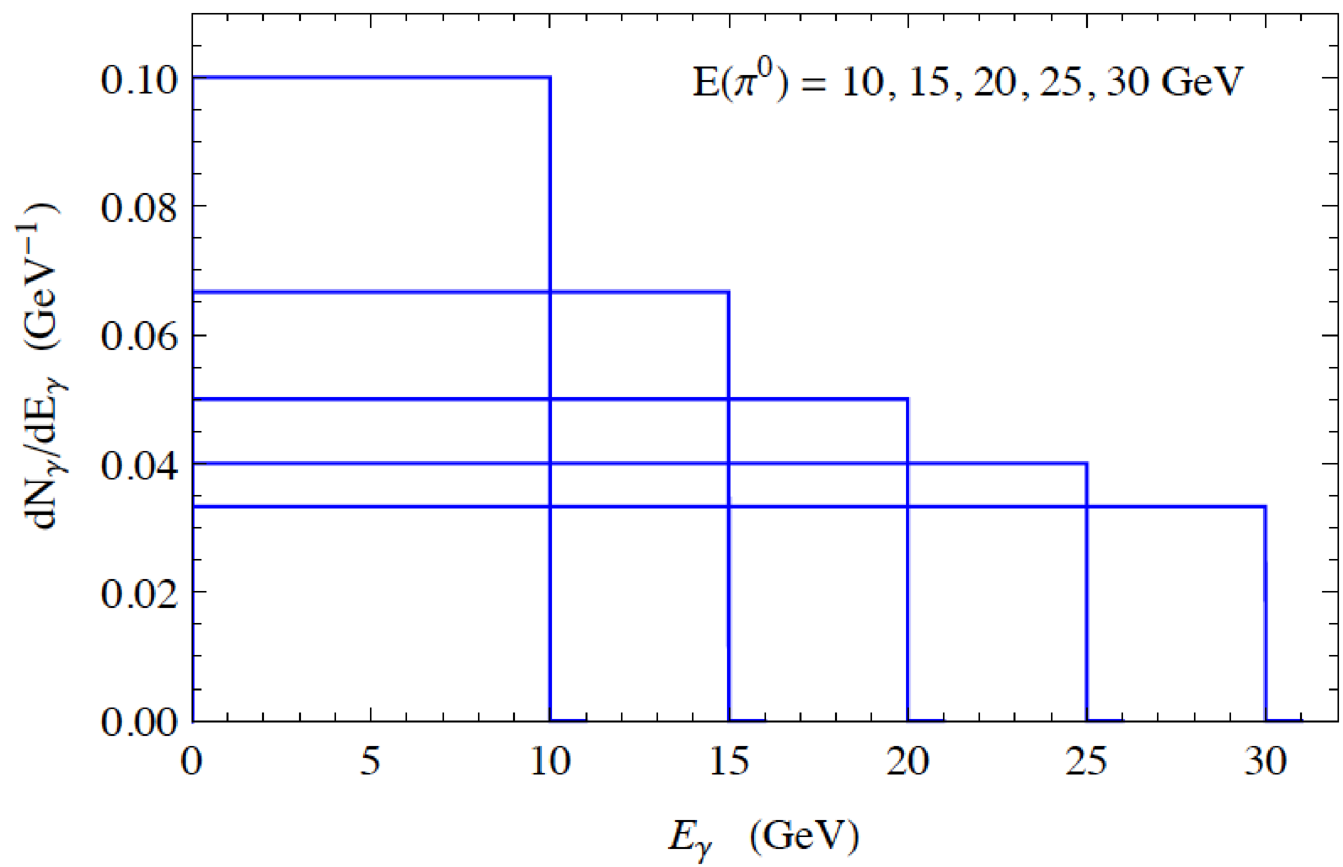
$$\frac{dN_\gamma}{dE_\gamma}(E_\gamma; E_\pi)$$

$$E_{\gamma,\min} = \frac{E_\pi}{2}(1 - \beta_\pi)$$

$$E_{\gamma,\max} = \frac{E_\pi}{2}(1 + \beta_\pi)$$

$$E_{\gamma,\min} \simeq 0$$

$$E_{\gamma,\max} \simeq E_\pi$$

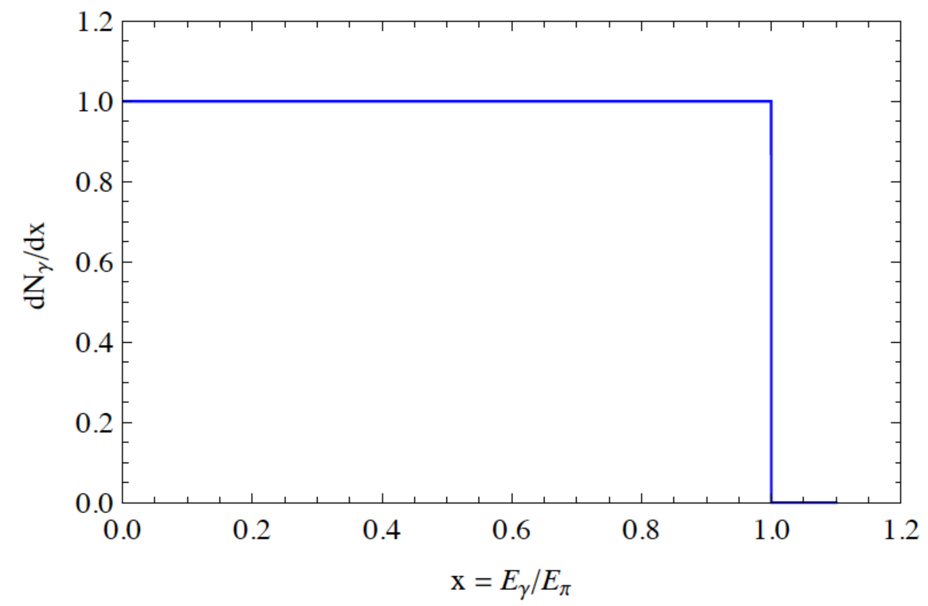


The spectrum of the photons has a

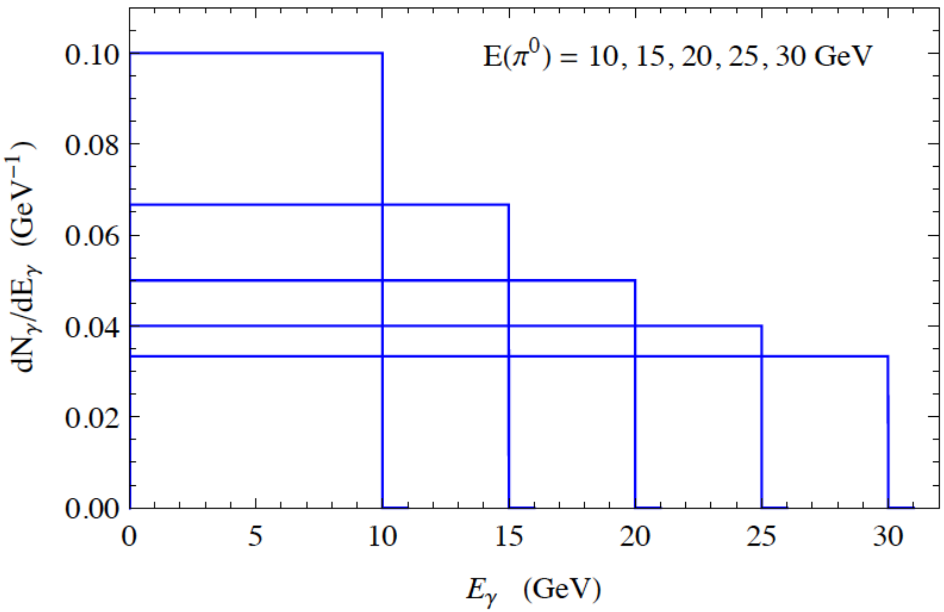
"scaling form"

$$\frac{dN_\gamma}{dE_\gamma}(E_\gamma; E_\pi)\Big|_{\pi^0\to\gamma\gamma} = \frac{1}{E_\pi}\, F_{\pi^0\to\gamma}\left(\frac{E_\gamma}{E_\pi}\right)$$

$$F_{\pi^0\to\gamma} = \begin{cases} 1 & \text{for} \quad x < 1 \\ 0 & \text{for} \quad x > 1 \end{cases}$$

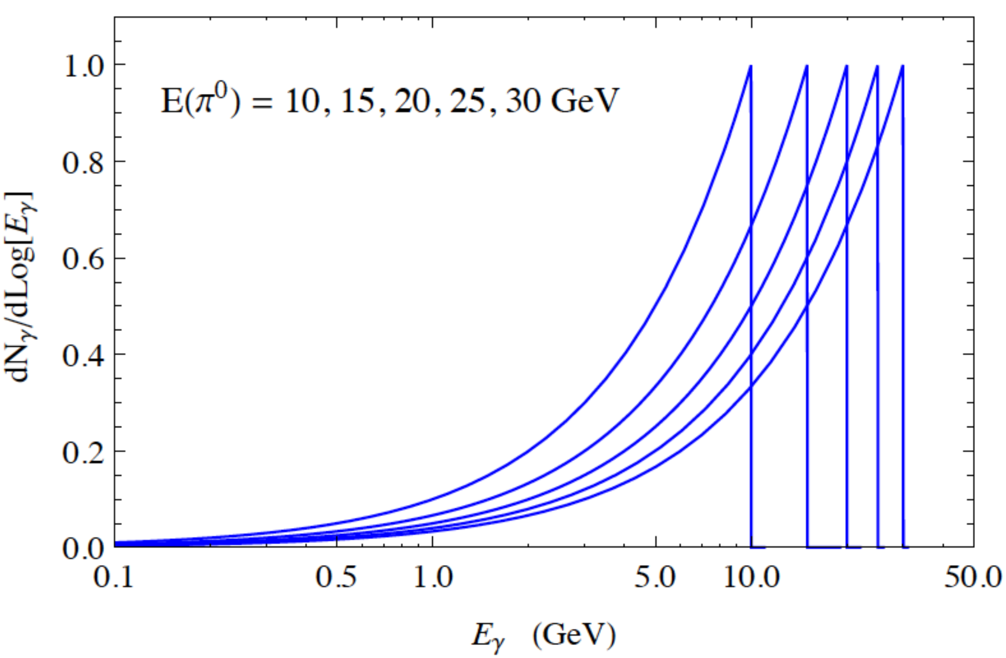


$$\frac{dN_\gamma}{dE_\gamma}$$

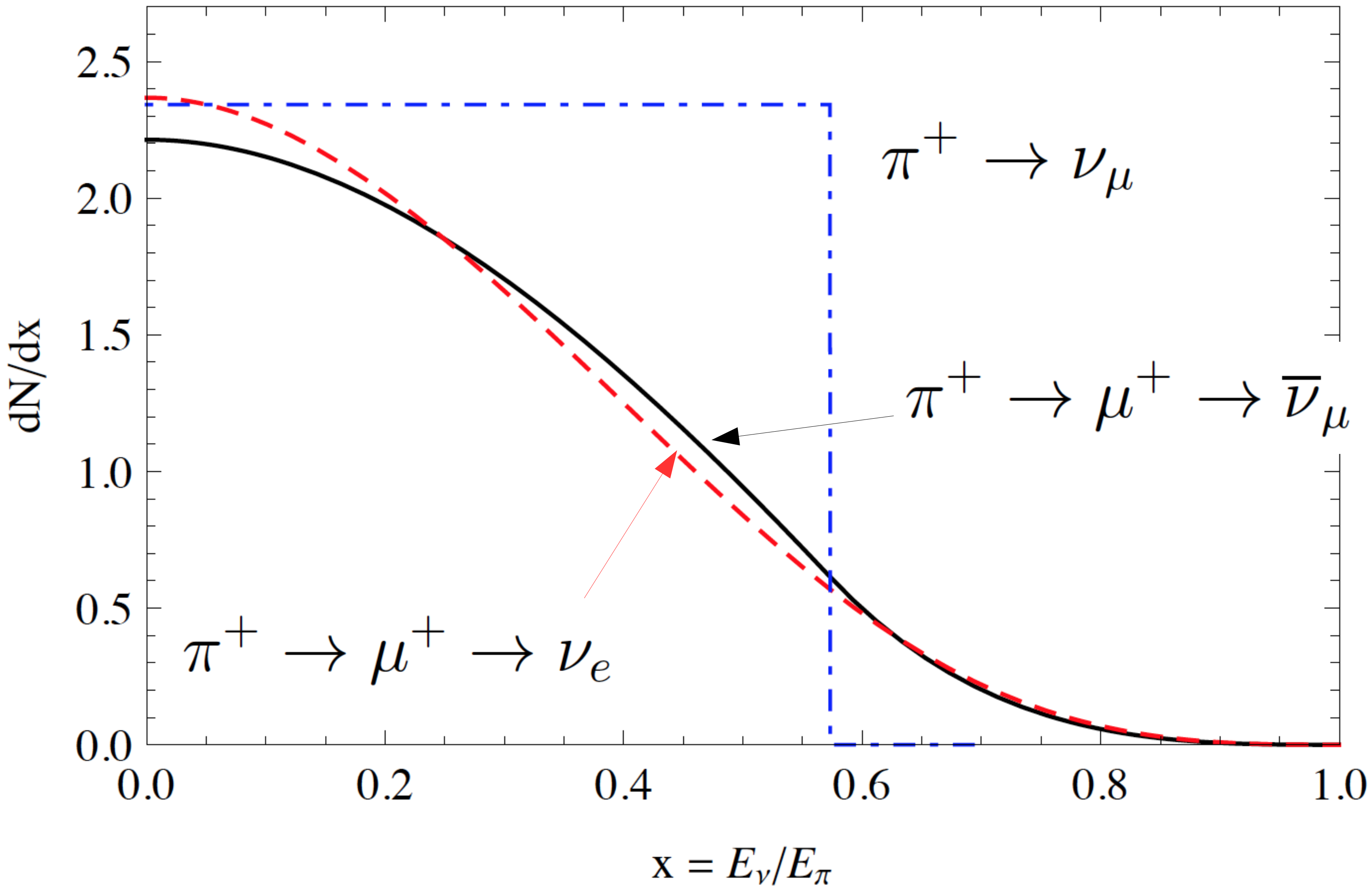


$$\frac{dN_\gamma}{d\ln E_\gamma} = E_\gamma \, \frac{dN_\gamma}{dE_\gamma}$$

Functions of same shape



Neutrino spectra in pion decay



$$\left\langle x_{\pi^+\to\nu_\mu}\right\rangle = \frac{1-r_\pi}{2} \simeq 0.213$$

$$\left\langle x_{\pi^+\mu^+\to\overline{\nu}_\mu}\right\rangle = \frac{3+4\,r_\pi}{20} \simeq 0.264$$

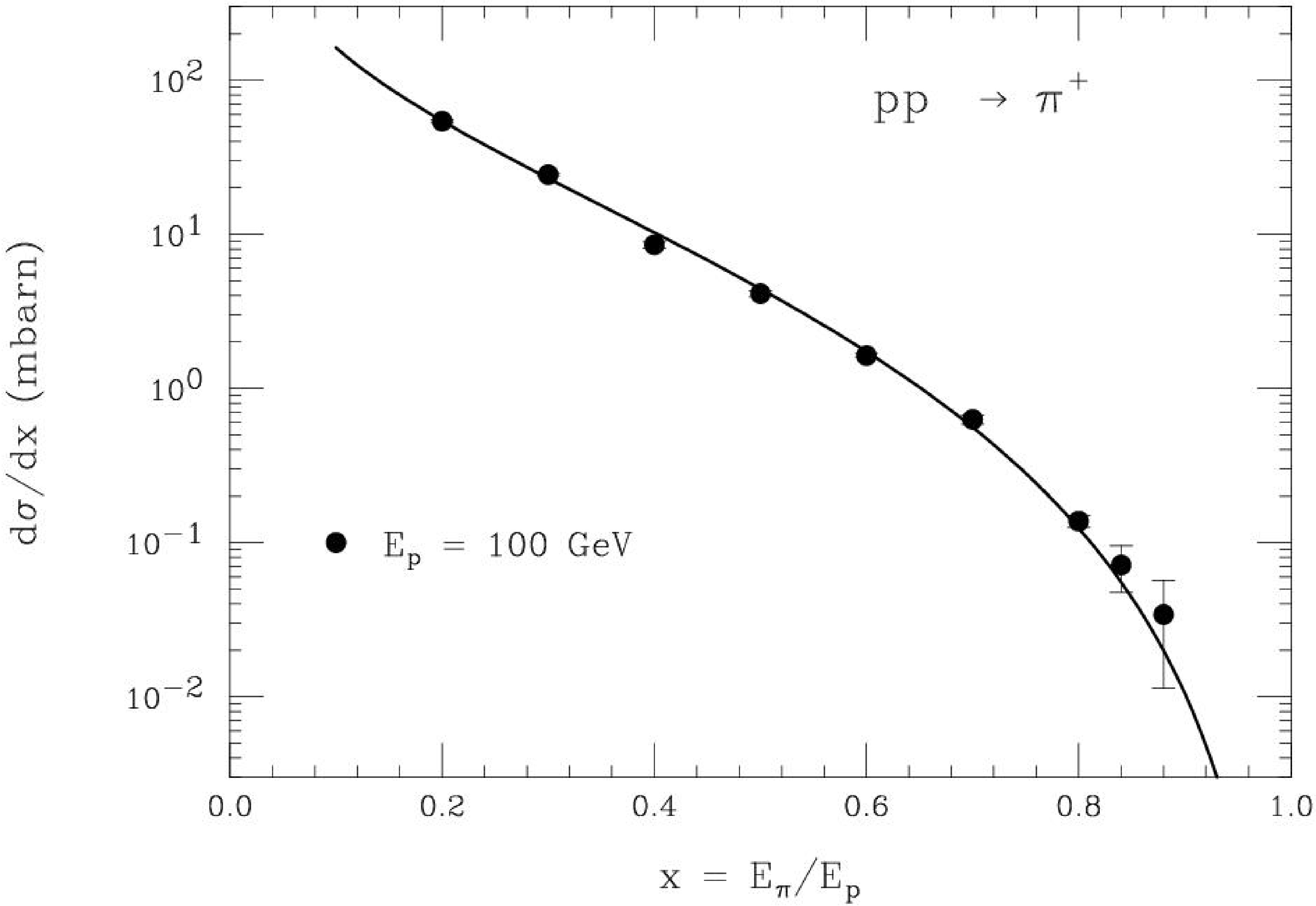
$$\left\langle x_{\pi^+\mu^+\to\nu_e}\right\rangle = \frac{2+r_\pi}{10} \simeq 0.257$$

$$\frac{dN_{p\to\gamma}}{dE_\gamma}(E_\gamma; E_p) = \frac{dN_{p\to\pi}}{dE_\pi}(E_\pi, E_p) \otimes \frac{dN_{\pi^0\to\gamma}}{dE_\gamma}(E_\gamma; E_\pi)$$

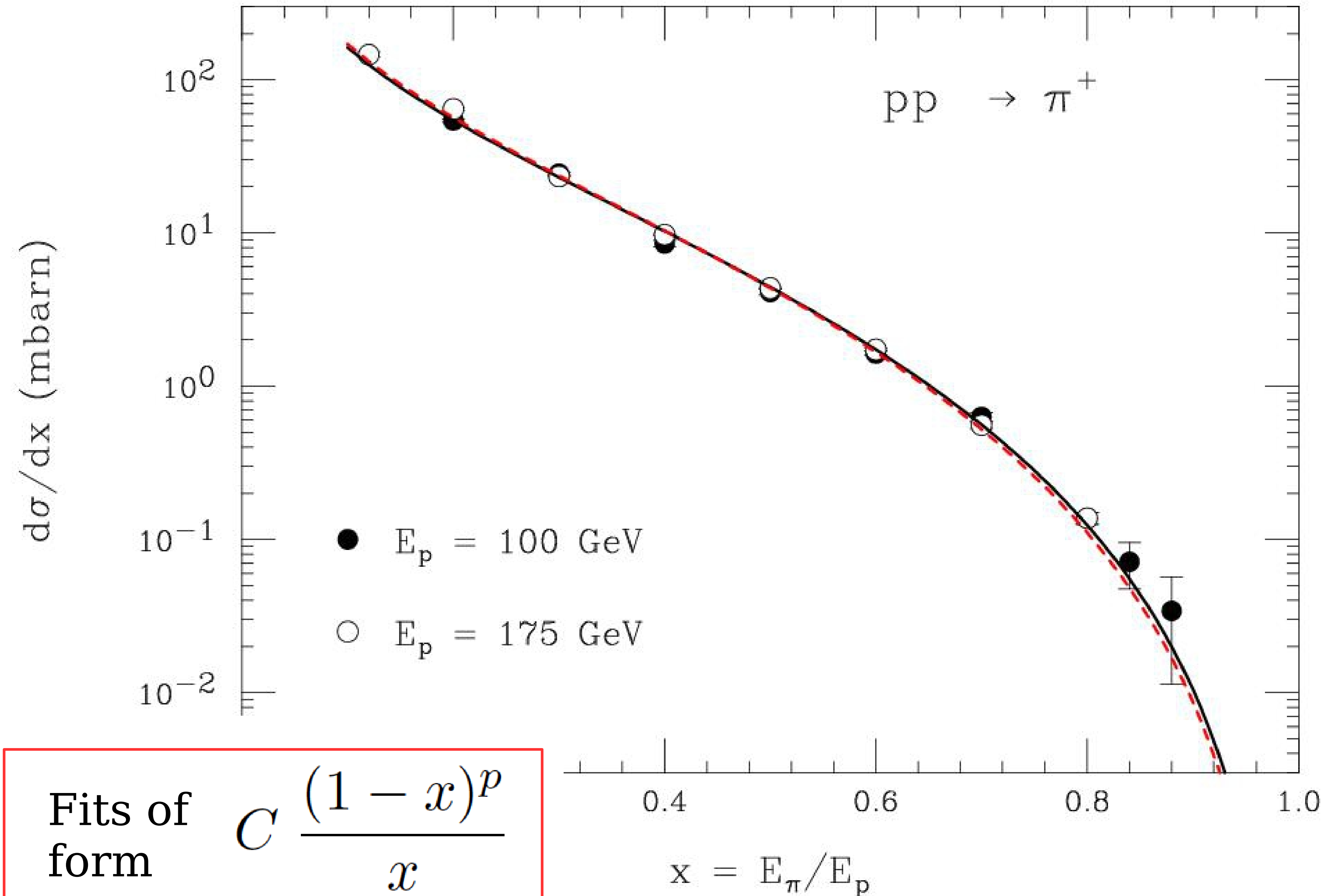
Inclusive distribution of pions
Produced in proton interactions

Fermilab Experiment

A.Brenner et al. Phys.Rev D26, 1497, (1982).



Two different Energies (100, 175 GeV)



Fits of form $C\,\dfrac{(1-x)^p}{x}$

Feynman Scaling

$$\frac{dn_{p\to\pi}}{dE_\pi}(E_\pi; E_0) = \frac{1}{E_0}\; F_{p\to\pi}\left(\frac{E_\pi}{E_0}\right)$$

(only approximate validity)

but very useful as “guide”
(and with important consequences)

$$\frac{dN_{p\to\gamma}}{dE_\gamma}(E_\gamma; E_p) = \frac{dN_{p\to\pi}}{dE_\pi}(E_\pi, E_p) \otimes \frac{dN_{\pi^0\to\gamma}}{dE_\gamma}(E_\gamma; E_\pi)$$

Inclusive distribution of pions
Produced in proton interactions

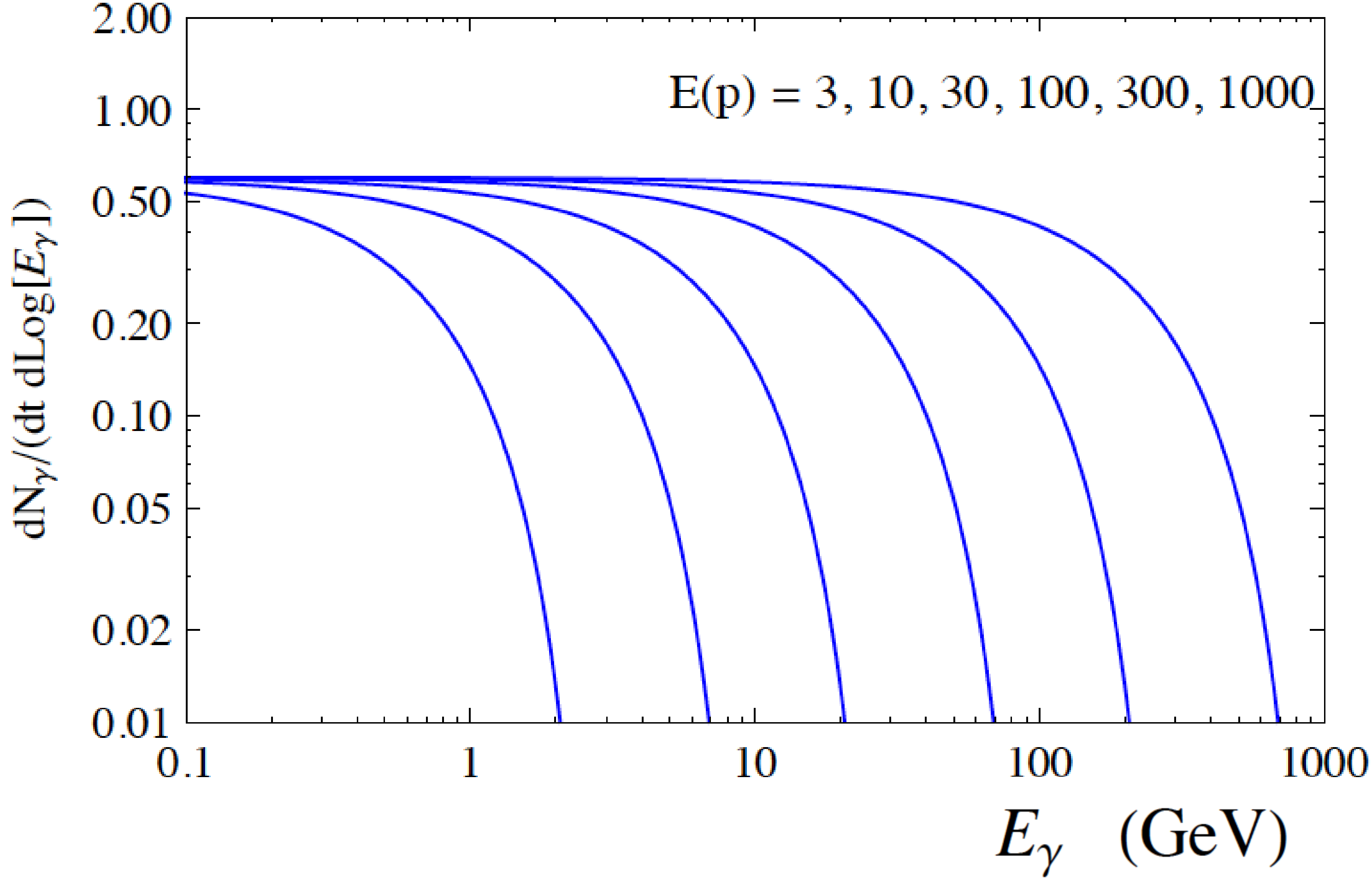
The convolution of two scaling functions
is again a scaling function

Important consequence :

A Power-Law spectrum of primary protons generates
power law spectrum of same exponent.

$$\left.\frac{dN_\gamma}{d\ln E_\gamma}\right|_{pp\to\gamma}(E_\gamma, E_p)$$

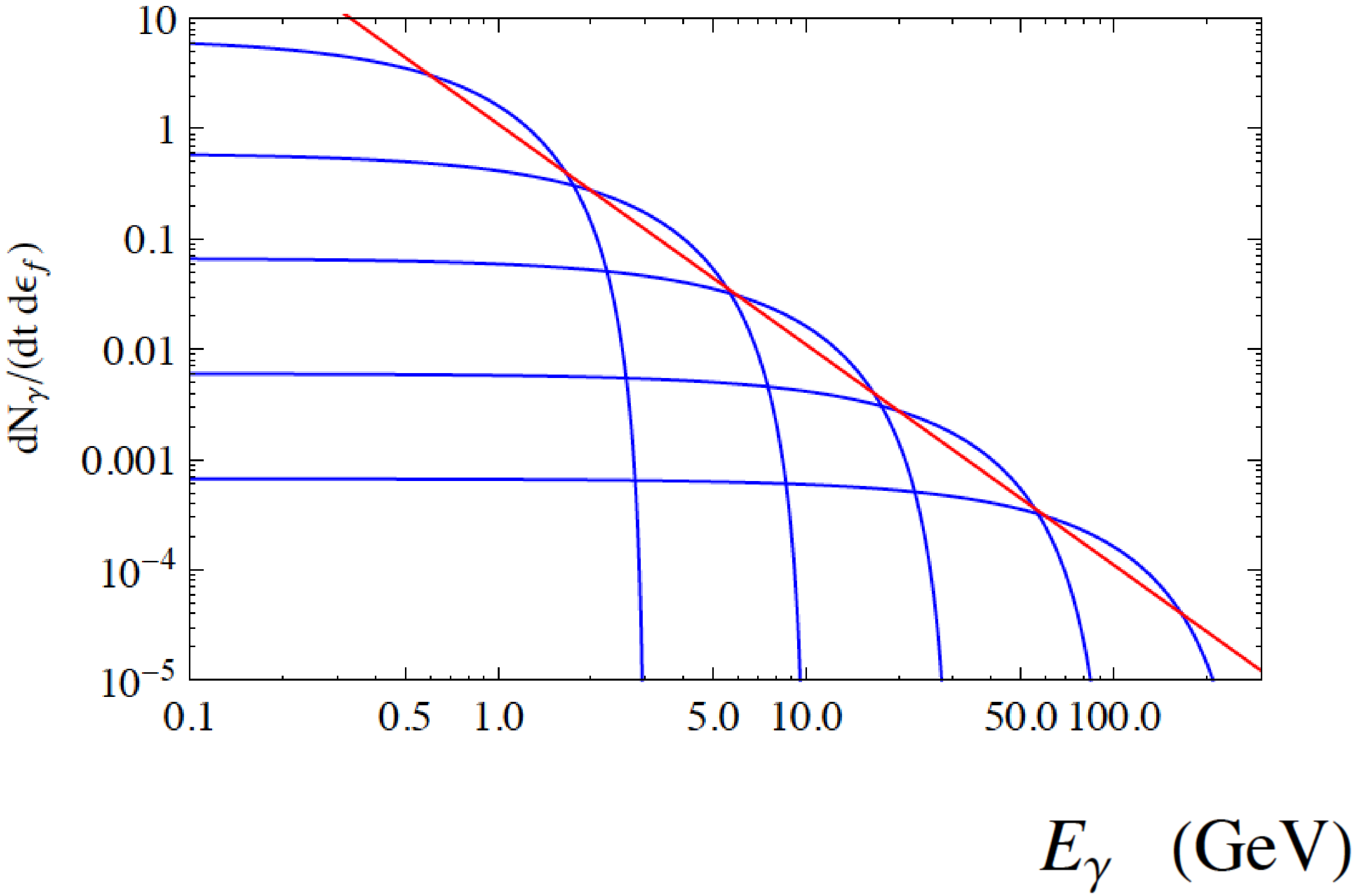
“Geometric demonstration”



$$E_p^{-2} \quad \left.\frac{dN_\gamma}{d\ln E_\gamma}\right|_{pp\to\gamma} (E_\gamma, E_p)$$

Weight all contributions with a power Law

Sum all contributions: obtain power Law of same exponent



$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \, \boxed{N_e(E_p)} \, \boxed{\frac{dP_{\text{int}}(E_p)}{dt}} \, \boxed{\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}}$$

Number of photons
emitted per unit time
and unit energy
at energy Eg

=

Number of protons
in the source with
Energy Ep

*

Probability that
one proton interact
per unit time

*

Number of photons
of energy Eg produced
in the interaction of
a proton of Energy Ep

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; \boxed{N_e(E_p)} \; \boxed{\frac{dP_{\text{int}}(E_p)}{dt}} \; \boxed{\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma}}$$

$$N_p(E) \simeq K \; E^{-\alpha}$$

$$\frac{dN_{p\to\gamma}(E_\gamma, E_p)}{dE_\gamma} \simeq \frac{1}{E_\gamma} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)$$

$$\frac{dP_{\text{int}}(E_p)}{dt} = \sigma_{pp}(E_p)\, n_p \; \beta c$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \;\; [K \; E_p^{-\alpha}] \;\; [n_p \; \sigma_{pp}(E)\, \beta c] \;\; \left[\frac{1}{E_p} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)\right]$$

$$\dot{N}_\gamma(E_\gamma) = \int_{E_\gamma}^{\infty} dE_p \; \left[K \; E_p^{-\alpha}\right] \; \left[n_p \; \sigma_{pp}(E) \; \beta c\right] \; \left[\frac{1}{E_p} \; F_{p\to\gamma}\left(\frac{E_\gamma}{E_p}\right)\right]$$

$$x = \frac{E_\gamma}{E_p}$$

$$dE_p = -dx \; \frac{E_\gamma}{x^2}$$

change of variables

Approximations:

v = c

$$\sigma_{pp}(E) \simeq \sigma_{pp}$$

$$\dot{N}_\gamma(E_\gamma) = n_p \, \sigma_{pp} \, c \int_0^1 dx \; \frac{E_\gamma}{x} \; K \; \left(\frac{E_\gamma}{x}\right)^{-\alpha} \; \left[\frac{x}{E_\gamma} \; Fp \to \gamma\,(x)\right]$$

$$\dot{N}_\gamma(E_\gamma) = n_p\,\sigma_{pp}\,c \int_0^1 dx\, \frac{E_\gamma}{x}\, K\, \left(\frac{E_\gamma}{x}\right)^{-\alpha} \left[\frac{x}{E_\gamma}\, Fp \to \gamma\,(x)\right]$$

$$\dot{N}_\gamma(E_\gamma) = n_p\,\sigma_{pp}\,c\; K\; E_\gamma^{-\alpha} \int_0^1 dx\; x^{\alpha-1}\; F_{p\to\gamma}\,(x)$$

$$\int_0^1 dx\; x^{\alpha-1}\; F_{p\to\gamma}\,(x) = Z_{p\to\gamma}(\alpha)$$

$$\dot{N}_\gamma(E_\gamma) = [K_p\,\sigma_{pp}\,c\,n_p\,Z_{p\to\gamma}]\; E_\gamma^{-\alpha}$$

$$\dot{N}_\gamma(E_\gamma) = \quad K_\gamma\; E_\gamma^{-\alpha}$$

3. Neutrinos versus Gamma Rays

- Ratio $(\nu + \overline{\nu})/\gamma$
- Ratio $\nu/\overline{\nu}$
- Gamma Ray "Leptonic emission"
- Gamma Ray absorption

IF the population of relativistic protons
inside an astrophysical source is a power law
of exponent alpha

$$N_p(E) \simeq K\ E^{-\alpha}$$

Then to a reasonably good approximation
the neutrino and photon emissions are also power laws
with the same exponent.

$$\dot{N}_\nu(E_\nu) \simeq K_\nu\ E_\nu^{-\alpha}$$

$$\dot{N}_\gamma(E_\gamma) = K_\gamma\ E_\gamma^{-\alpha}$$

$$\boxed{\begin{aligned}\dot{N}_\nu(E_\nu) &= K_\nu \; E_\nu^{-\alpha} \\ &\simeq K_p \, \sigma_{pp} \, c \, n_{\rm gas} \; Z_{pp\to\nu}(\alpha) \quad E_\nu^{-\alpha}\end{aligned}}$$

$$Z_{pp\to\nu}(\alpha) \simeq \; Z_{pp\to\pi^\pm}(\alpha) \times Z_{\pi^\pm\to\nu}(\alpha)$$

$$\frac{dN_{a\to b}}{dE_a} \simeq \frac{1}{E_b}\, F_{a\to b}\left(\frac{E_a}{E_b}\right)$$

$$Z_{a\to b}(\alpha) = \int_0^1 dx\; x^{\alpha-1}\; F_{a\to b}(x)$$

$$Z_{a\to b}(\alpha = 1) = \langle N_b \rangle$$

$$Z_{a\to b}(\alpha = 2) = \langle x_b \rangle = \frac{\langle E_b \rangle}{E_a}$$

“Isospin symmetry”

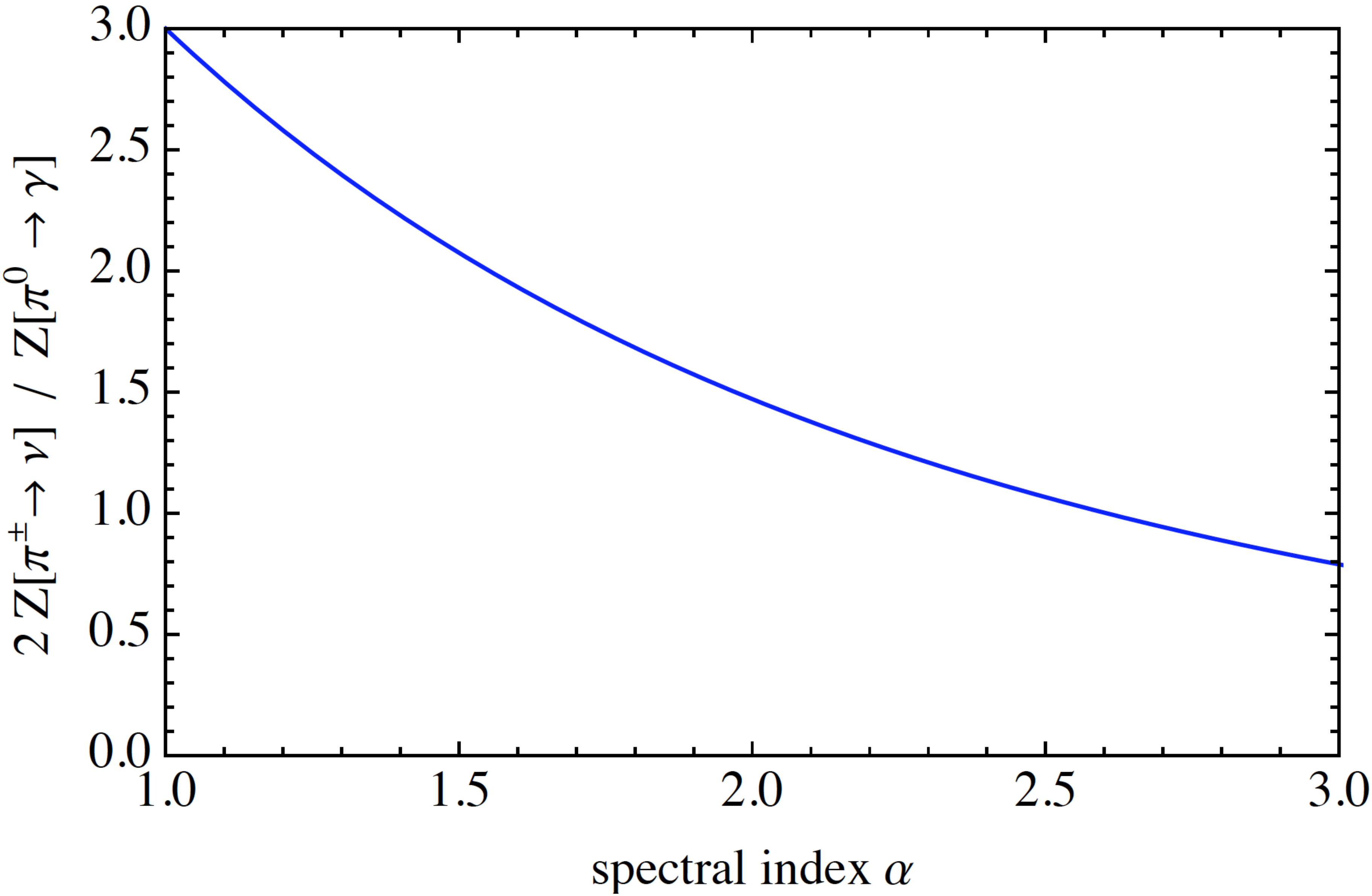
$$\pi^{+} \simeq \pi^{-} \simeq \pi^{\circ}$$

$$Z_{pp\to\pi^+} \simeq Z_{pp\to\pi^-} \simeq Z_{pp\to\pi^0}$$

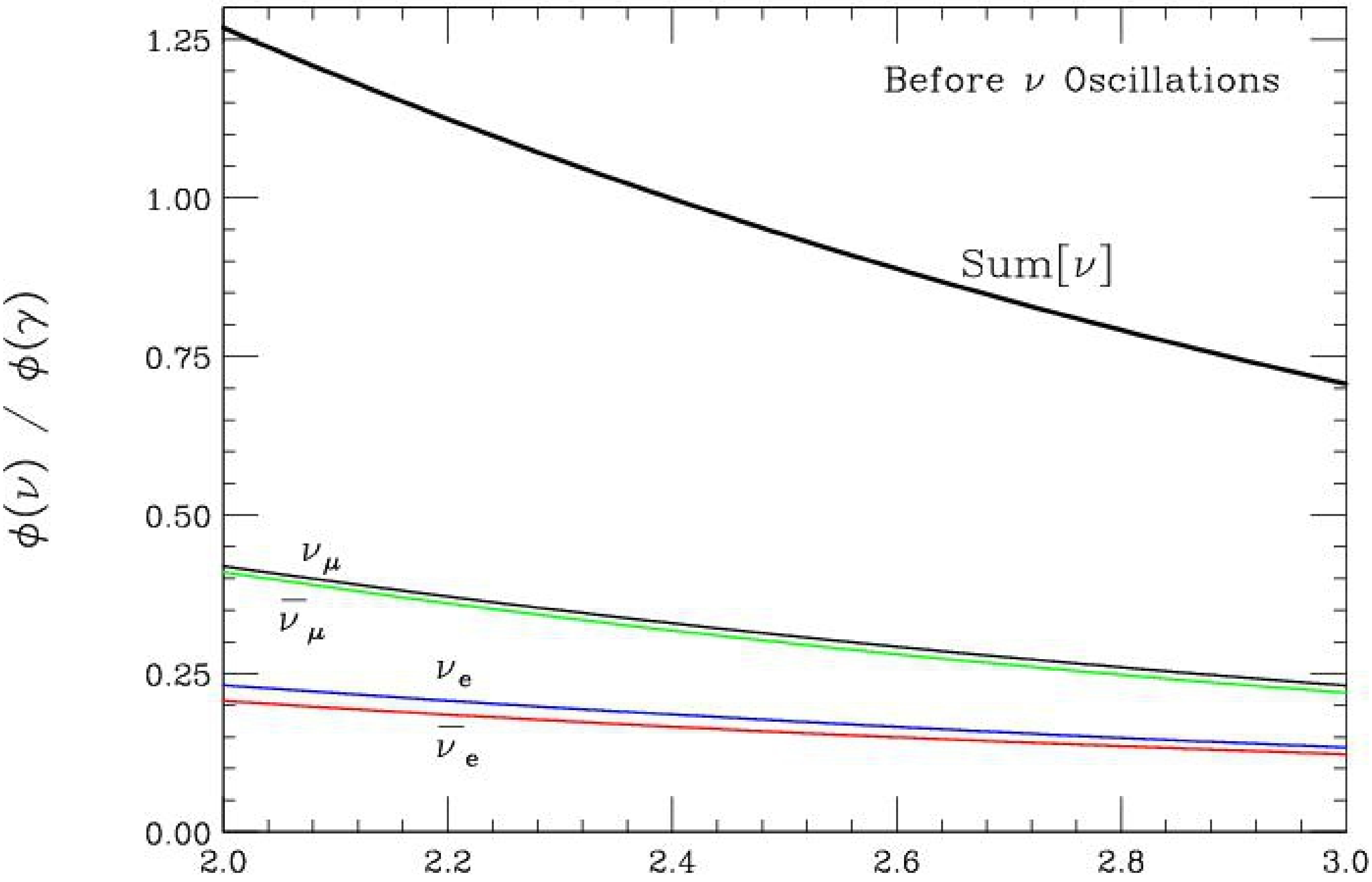
$$\frac{\nu}{\gamma} \simeq \frac{2\ Z_{\pi^{\pm}\to\nu}}{Z_{\pi^0\to\gamma}}$$

Ratio Neutrinos/Photon
(pion production dominated)

$\phi(\nu) \ / \ \phi(\gamma)$



Ratio Neutrino-Photon (numerical calculation)



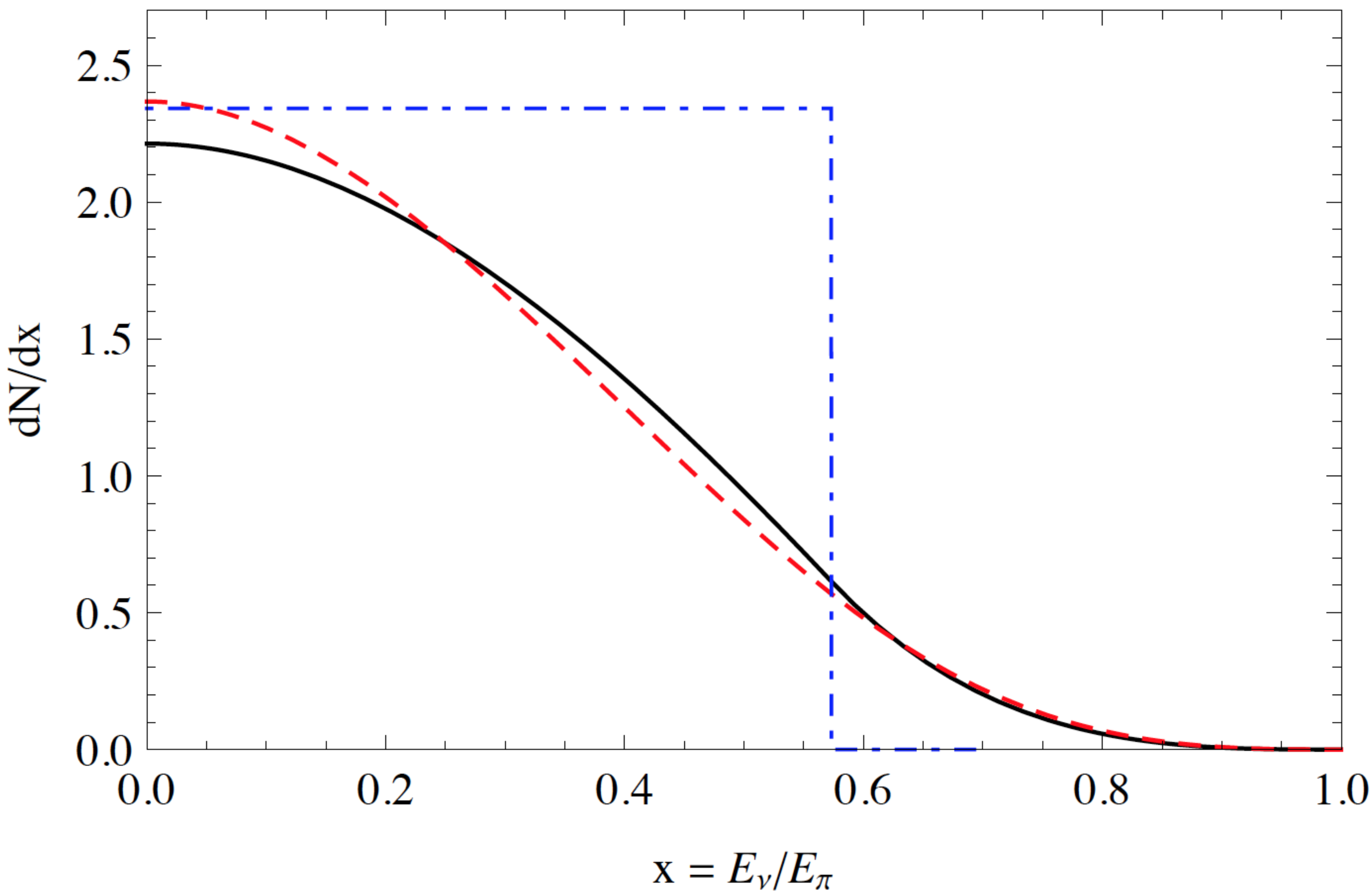
$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

“Signature” of the hadronic mechanism:

The mass m_{π° leaves its “imprint”

on the photon spectrum

Look again to the decay spectrum

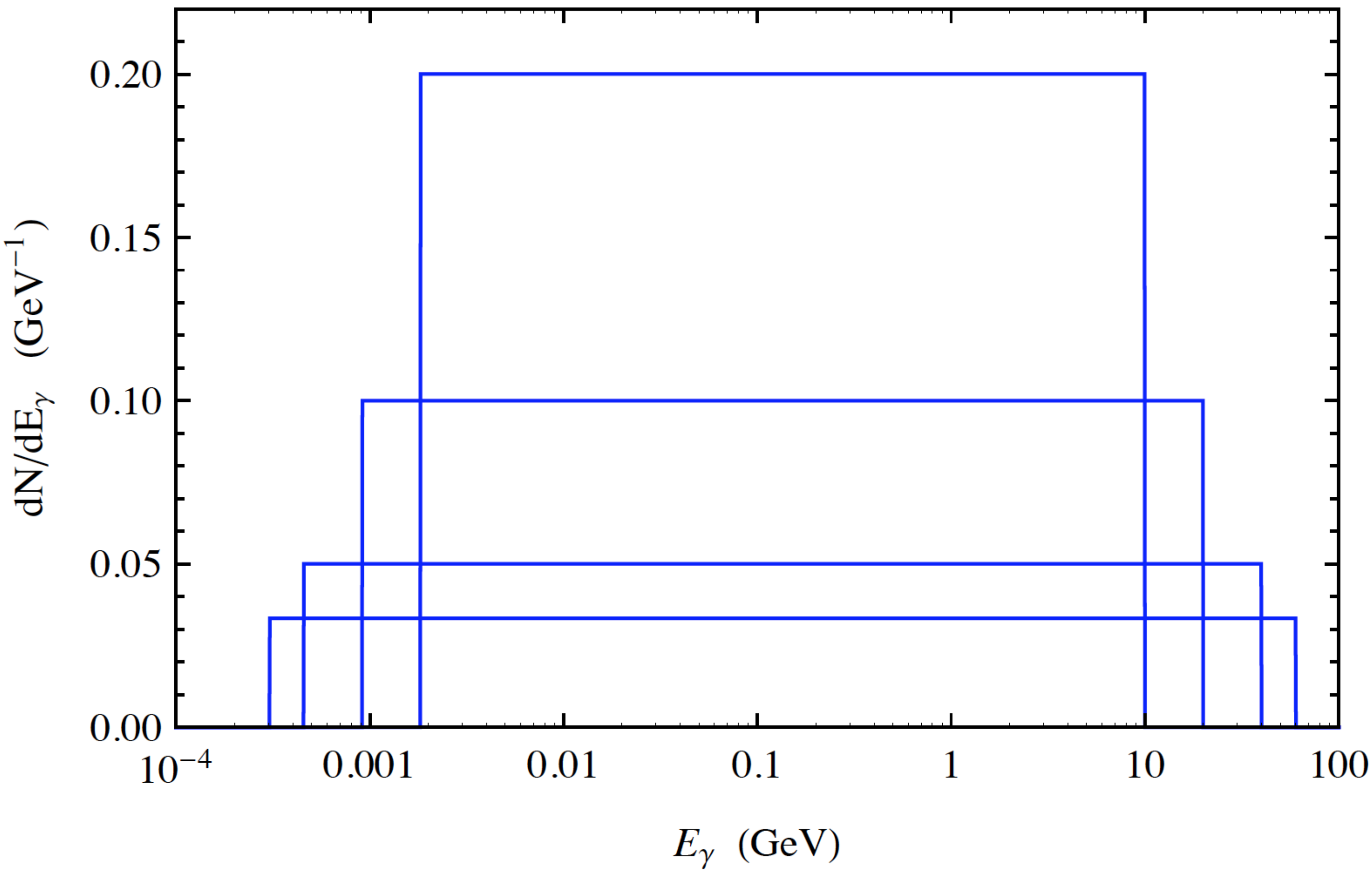


2.5
2.0
1.5
1.0
0.5
0.0
dN/dx
0.0
0.2
0.4
0.6
0.8
1.0
x = E_ν/E_π

$$E_{\gamma,\min} = E_\pi \, (1 - \beta_\pi)$$

$$E_{\gamma,\max} = E_\pi \, (1 + \beta_\pi)$$

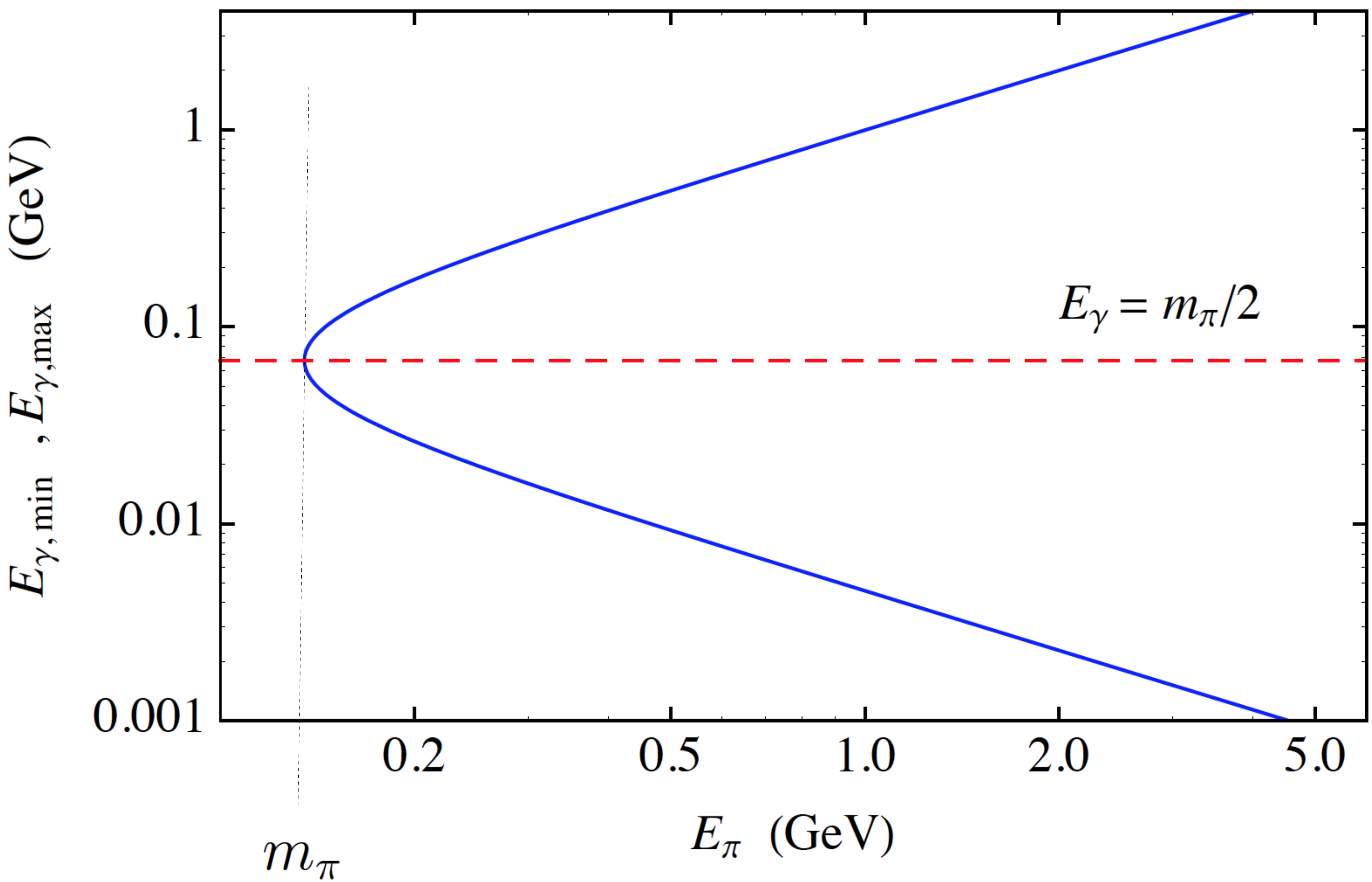
$$E_{\gamma \ \min,(\max)} = E_\pi \, \left(1 \mp \sqrt{1 - \frac{m_\pi^2}{E_\pi^2}}\right)$$



Low energy photons can only be produced by High energy pions

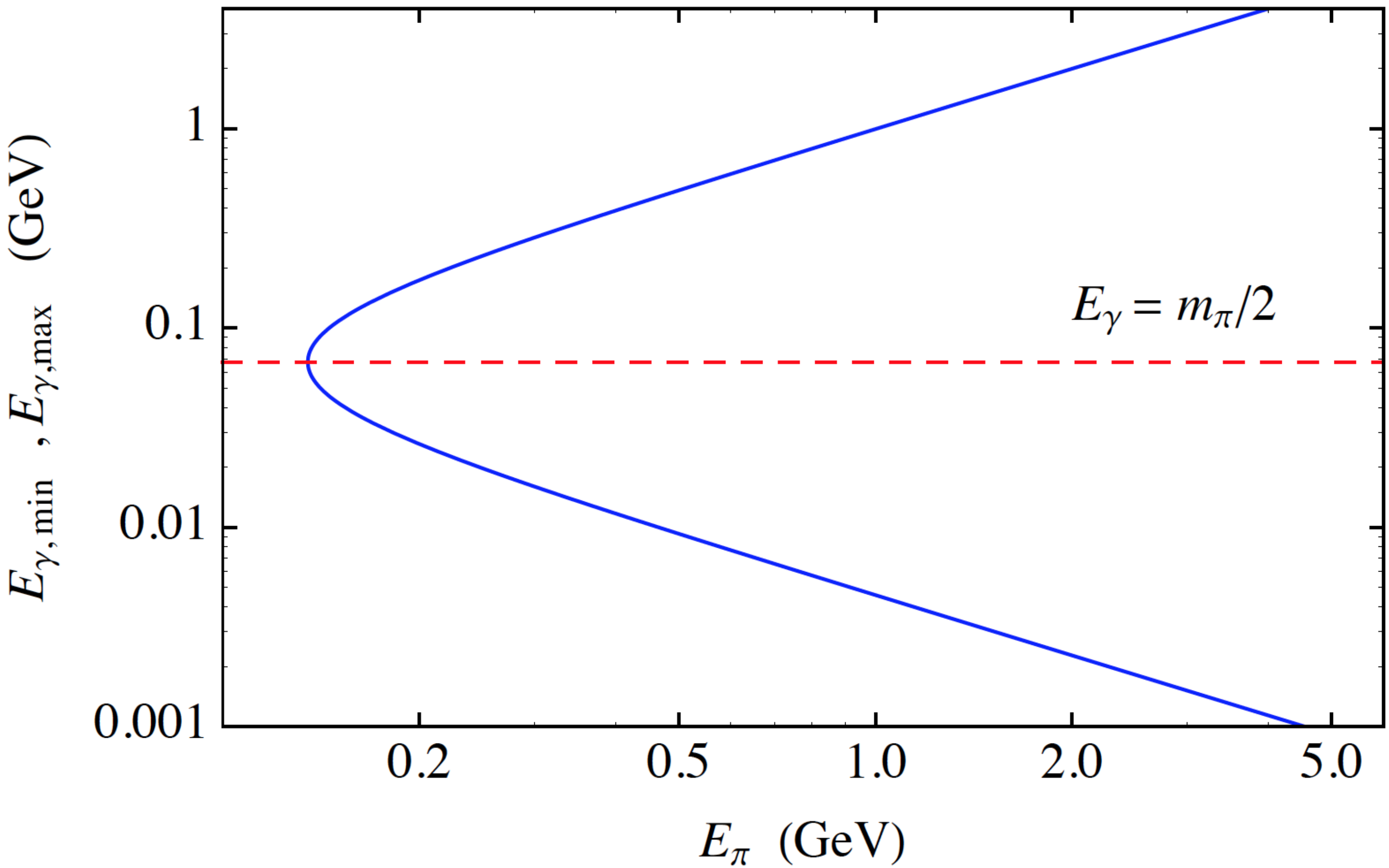
$$E_{\gamma,\min} = E_\pi \, (1 - \beta_\pi)$$

$$E_{\gamma,\max} = E_\pi \, (1 + \beta_\pi)$$



$$E_{\pi,\min}(E_\gamma) = E_\gamma + \frac{m_\pi^2}{4\,E_\gamma} \;= \frac{m_\pi}{2}\;\left[\frac{2E_\gamma}{m_\pi} + \frac{m_\pi}{2\,E_\gamma}\right]$$

[symmetry for "reflections" around $E_\gamma = m_{\pi^\circ}/2$]



Gamma ray spectrum as convolution of the π° spectra

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma) = \int_{E_{\pi,\min}(E_\gamma)}^{\infty} dE_\pi \; \frac{dN_\pi}{dE_\pi}(E_\pi) \; \frac{dN_{\pi^\circ\to\gamma}}{dE_\gamma}(E_\gamma, E_\pi)$$

$$= \int_{E_\gamma + m_\pi^2/(4\,E_\gamma)}^{\infty} dE_\pi \; \frac{dN_\pi}{dE_\pi}(E_\pi) \; \frac{1}{\sqrt{E_\pi^2 - m_\pi^2}}$$

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma) = \frac{d\dot{N}_\gamma}{dE_\gamma}(E'_\gamma)$$

$$\frac{2E_\gamma}{m_\pi} = \frac{m_\pi}{2\,E'_\gamma}$$

For the *hadronic emission mechanism*:

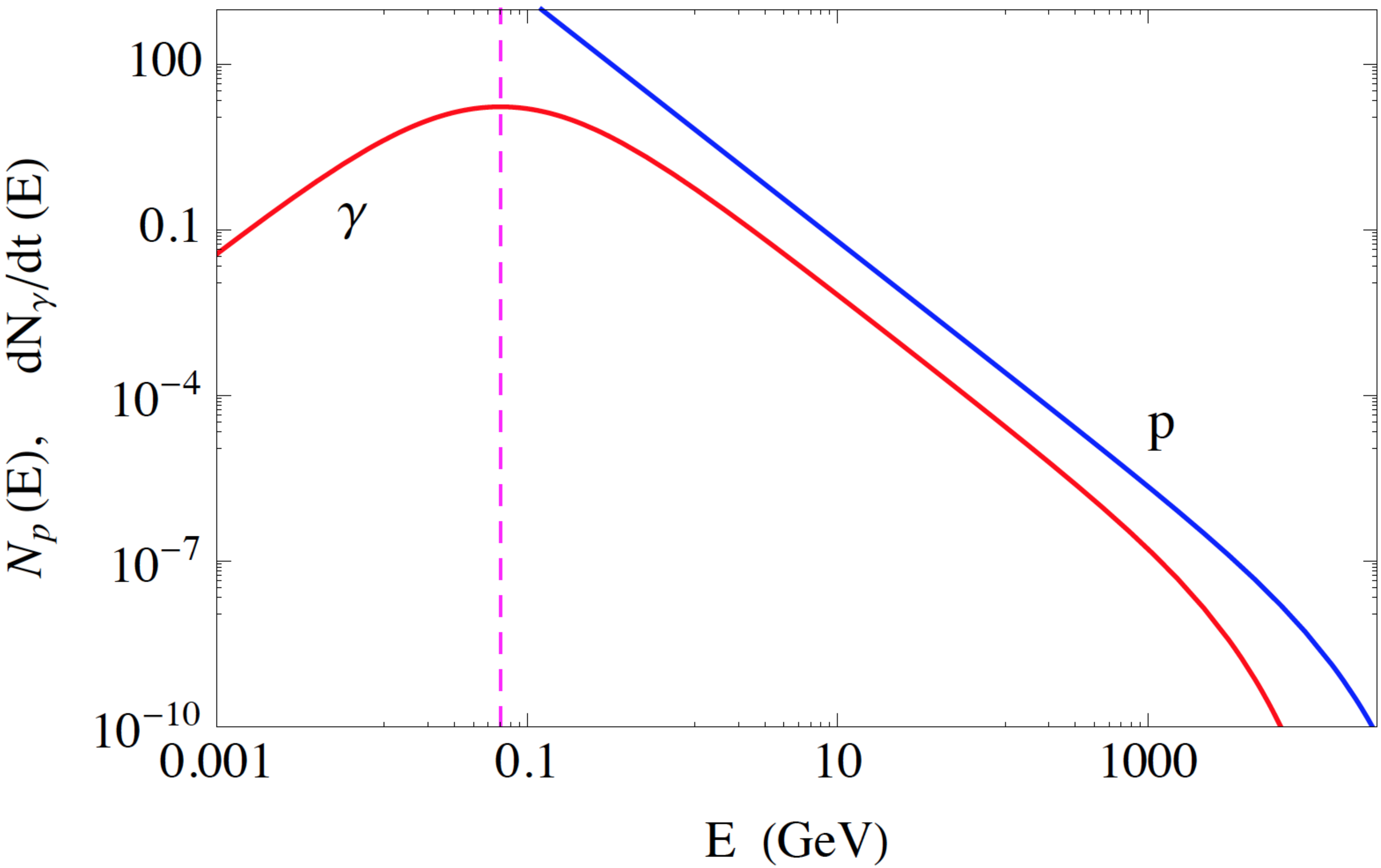
The photon spectra at energies E_γ and E'_γ symmetric around $m_{\pi^\circ}/2$ are *equal*.

Low energy cutoff

Consequence of
The pion mass = 0.135 GeV

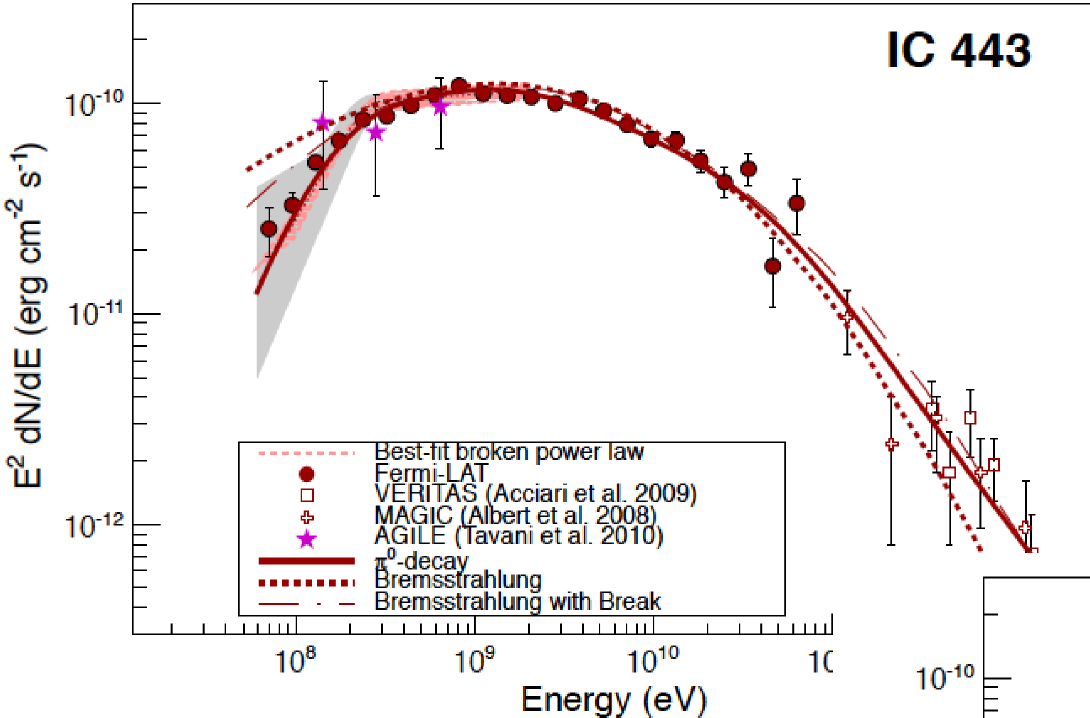
High energy cutoff:

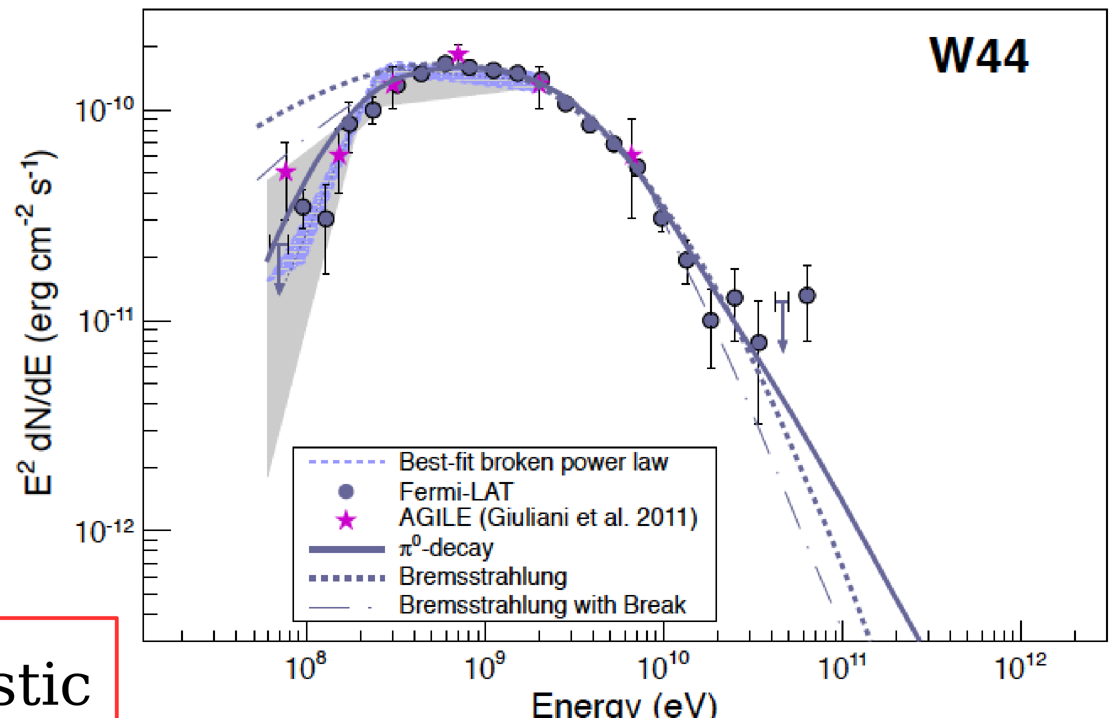
Reflects a possible cutoff in the
Proton spectrum



Result of the
FERMI collaboration

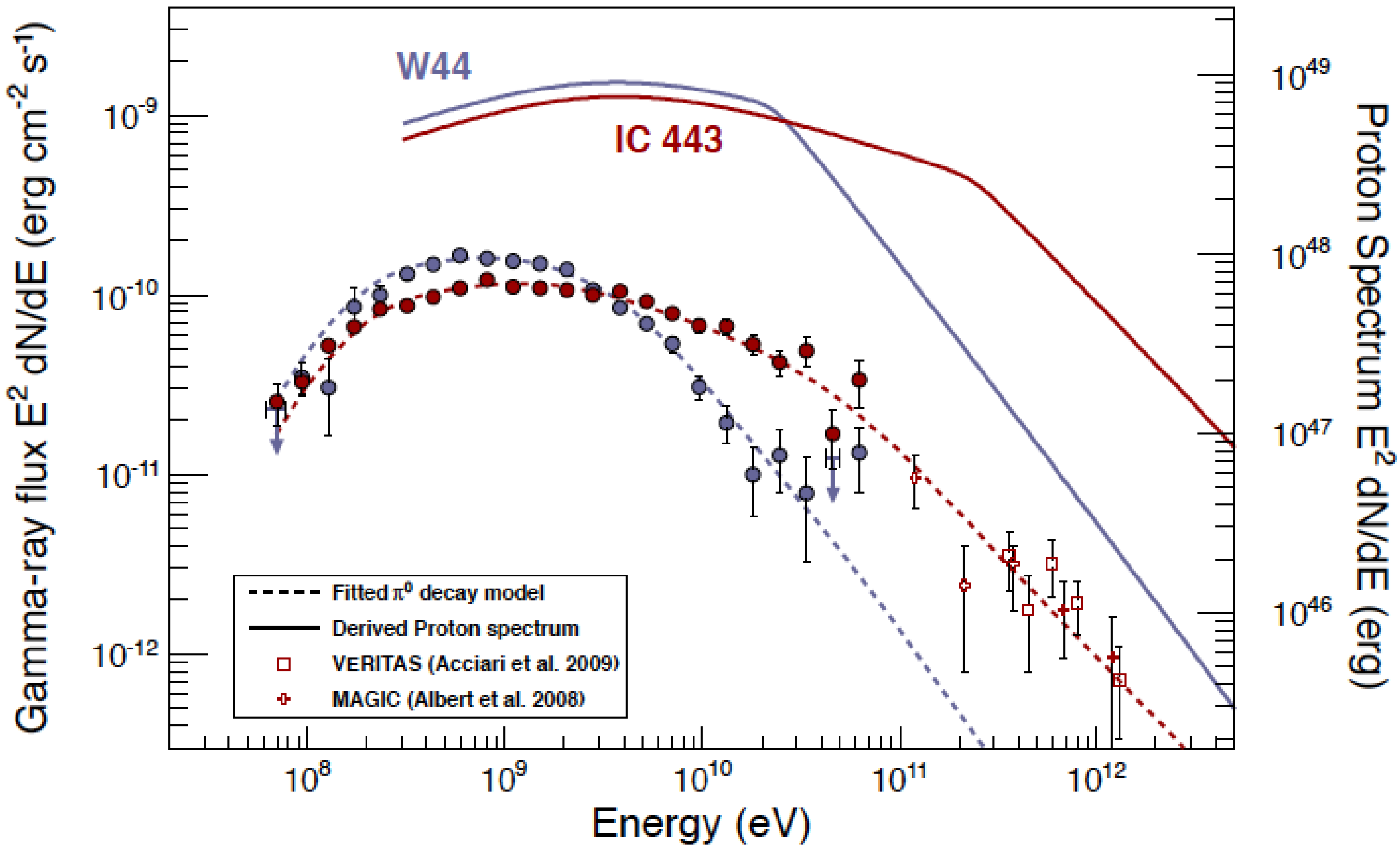
SCIENCE feb. 2013





"Detection of the characteristic Pion-decay signature in Supernova Remnants"

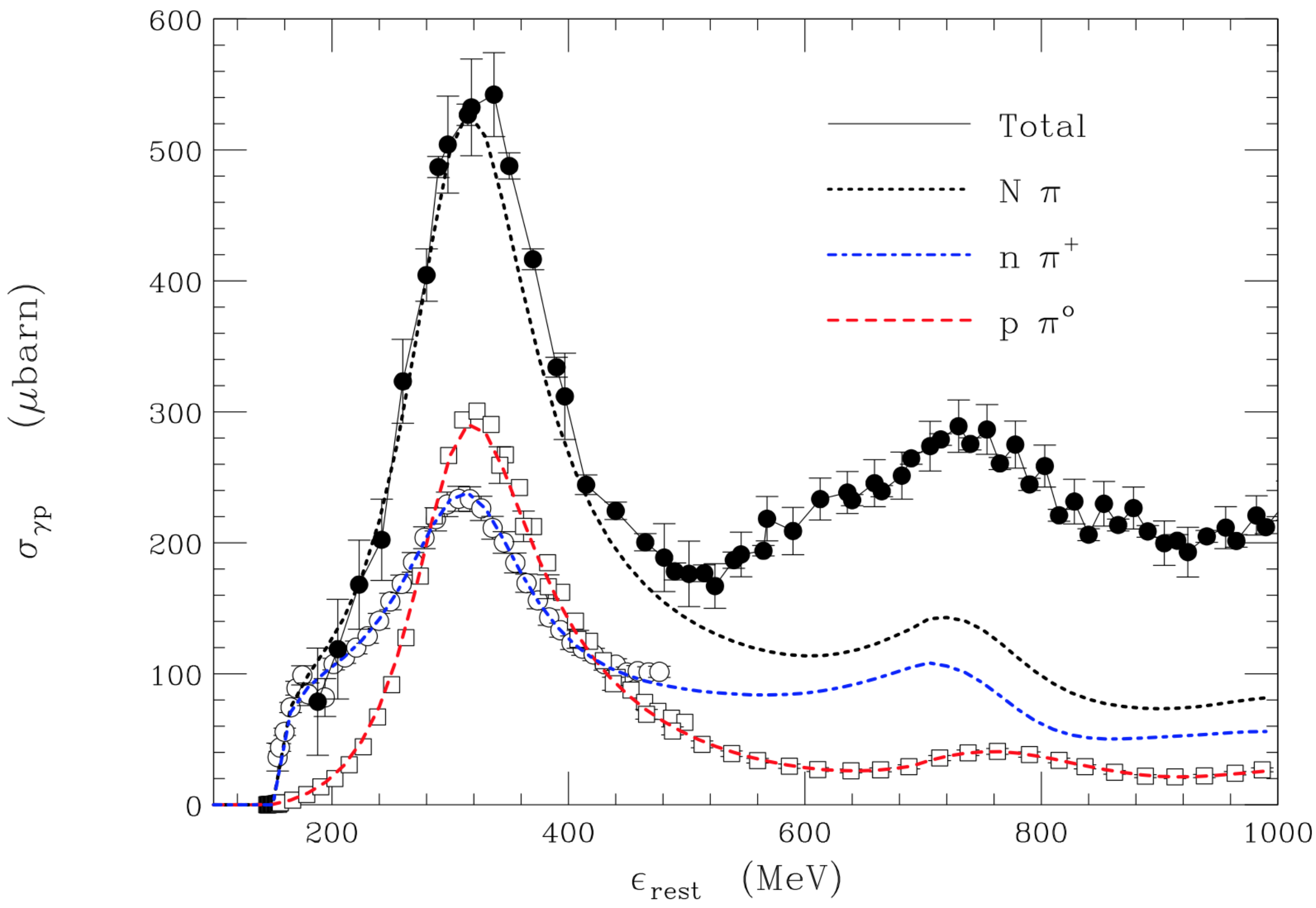
Reconstruction of the Proton population
Inside the two SuperNova shells



$p\gamma$ versus pp

Cross section

$$p + \gamma \to \text{hadrons}$$



$$p + \gamma \to n + \pi^+$$

$$p + \gamma \to p + \pi^0$$

Energy threshold for photo-production:
(creation of a single pion):

$$s_{p\gamma} \geq (m_p + m_\pi)^2$$

Rest frame of the proton

$$\varepsilon_{\rm rest} \geq m_\pi + \frac{m_\pi^2}{2\,m_p}$$

Laboratory Frame

$$4\,E\,\varepsilon \geq 2\,m_p\,m_\pi + m_\pi^2$$

$$\varepsilon \geq \frac{1}{4\,E_p}\,(2\,m_p\,m_\pi + m_\pi^2)$$

Proton interaction probability per unit time:

$$K_{p\gamma}(E_p) = \sigma_{p\gamma} \otimes n_\gamma(\varepsilon)$$

$$K_{p\gamma}(E_p) = \int d\varepsilon \int_{-1}^{+1} \frac{d\cos\theta_{p\gamma}}{2} \,(1-\cos\theta_{p\gamma})\, n_\gamma(\varepsilon,\cos\theta_{p\gamma})\, \sigma_{p\gamma}(\varepsilon_r)$$

Target photon distribution
has approximately a power form:

$$n_\gamma(\varepsilon) \propto \varepsilon^{-\beta}$$

$$K_{p\gamma}(E_p) \propto E^{\beta}$$

Interaction probability
that grows with energy
reflecting the target photon
spectral shape

Neutrino emission:

$$\frac{d\dot{N}_\nu}{dE} \propto E_\nu^{-\alpha+\beta-1}$$

$$\frac{d\dot{N}_\nu}{dE} \propto E_\nu^{-\alpha_\nu}$$

$$\alpha_\nu \simeq \alpha - \beta + 1$$

Spectral index of the neutrinos
reflects the spectral indices
of the interacting protons
and of the target photons

Signatures for a $p\gamma$ mechanism of neutrino production:

[Dominance of single pion production]

$$p + \gamma \to n + \pi^+$$

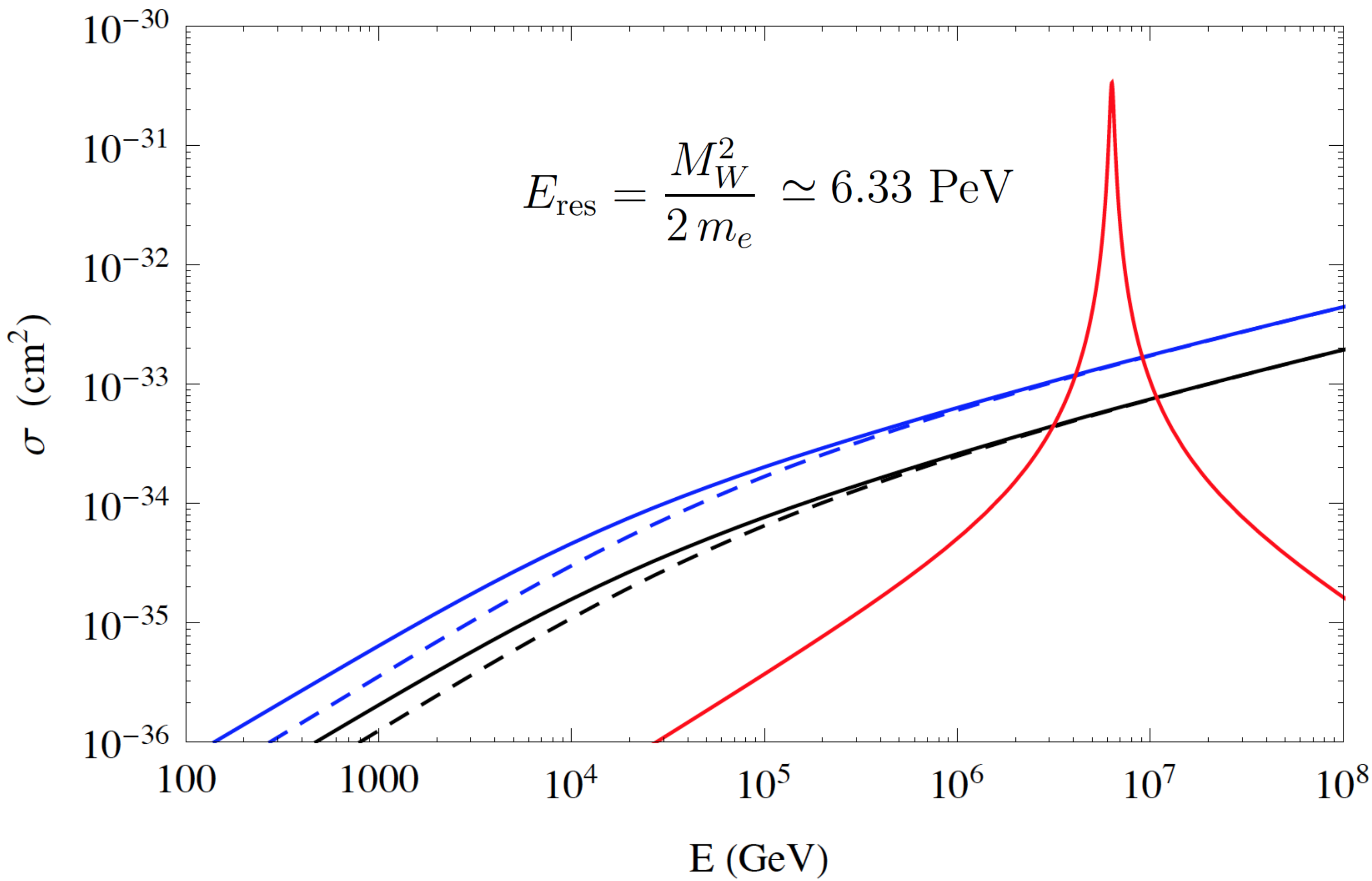
$$p + \gamma \to p + \pi^0$$

$$\frac{(\nu + \overline{\nu})}{\gamma} \simeq 2$$

$$\frac{\nu}{\overline{\nu}} \simeq 2$$

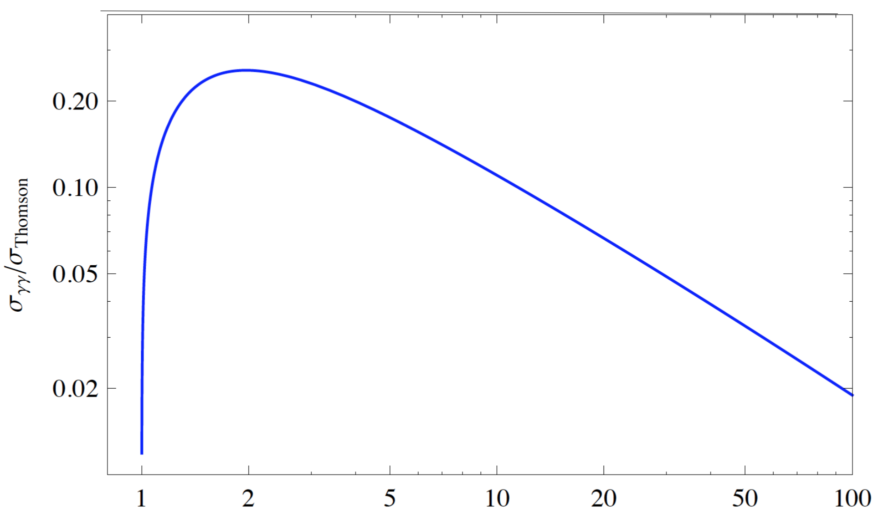
Neutrino Cross section

$$\overline{\nu}_e + e^- \to W^{-*} \to \text{hadrons}$$
$$\to \mu^- + \overline{\nu}_\mu$$



Gamma Ray Absorption:

$$\gamma + \gamma \to e^+ + e^-$$



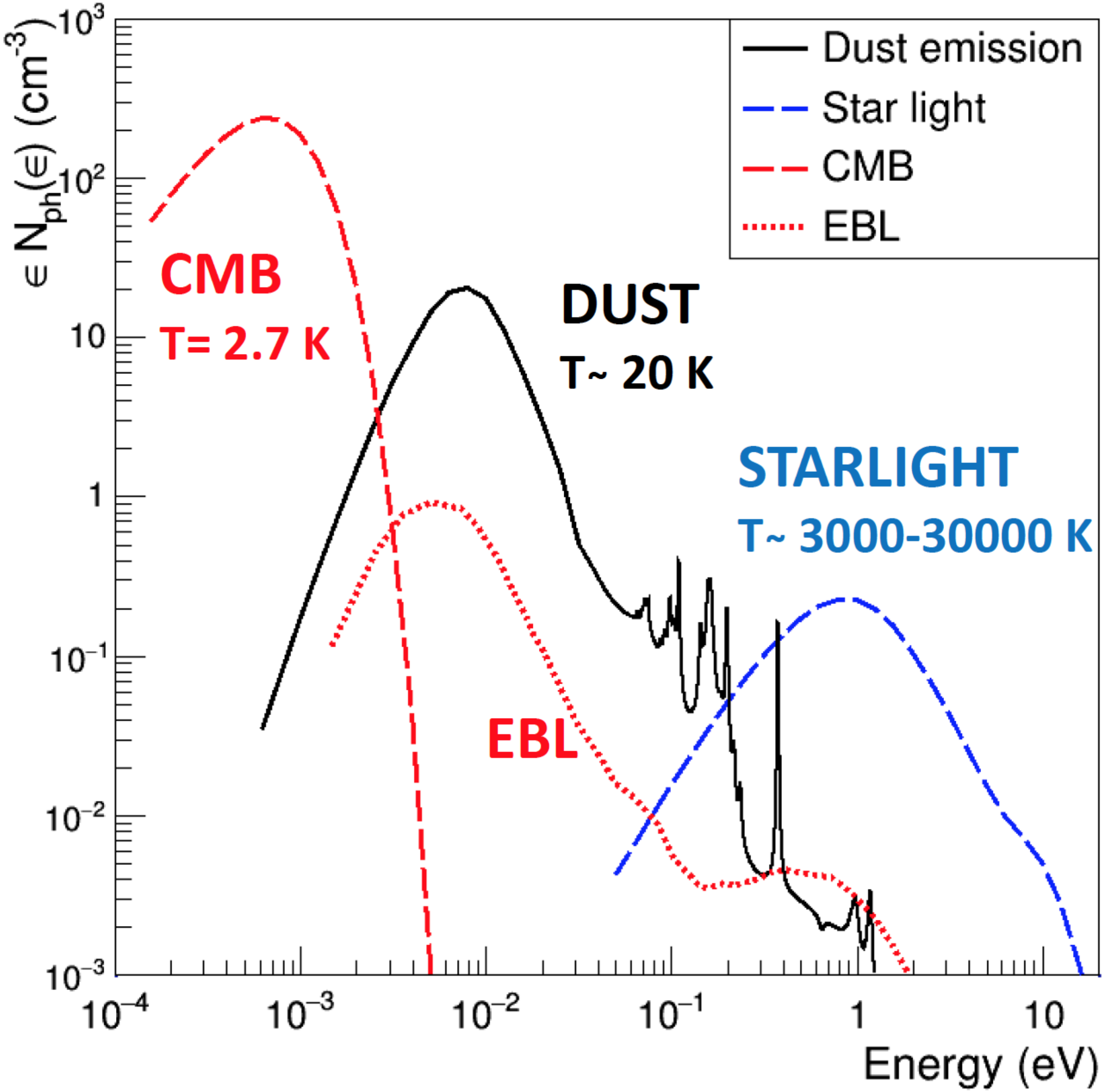
$$x = s/(4m_e^2)$$

$$x = \frac{s}{4\,m_e^2} = \frac{E_\gamma\,\varepsilon\,(1-\cos\theta_{\gamma\gamma})}{2\,m_e^2}$$

$$\sigma_{\gamma\gamma}^{\text{max}} \simeq 0.2554\ \sigma_{\text{Th}}$$

$$\simeq 1.70 \times 10^{-25}\ \text{cm}^2$$

Local (Solar neighborhood) Radiation fields



$$N_\gamma^{\rm CMBR} \simeq 410.7 \text{ cm}^{-3}$$

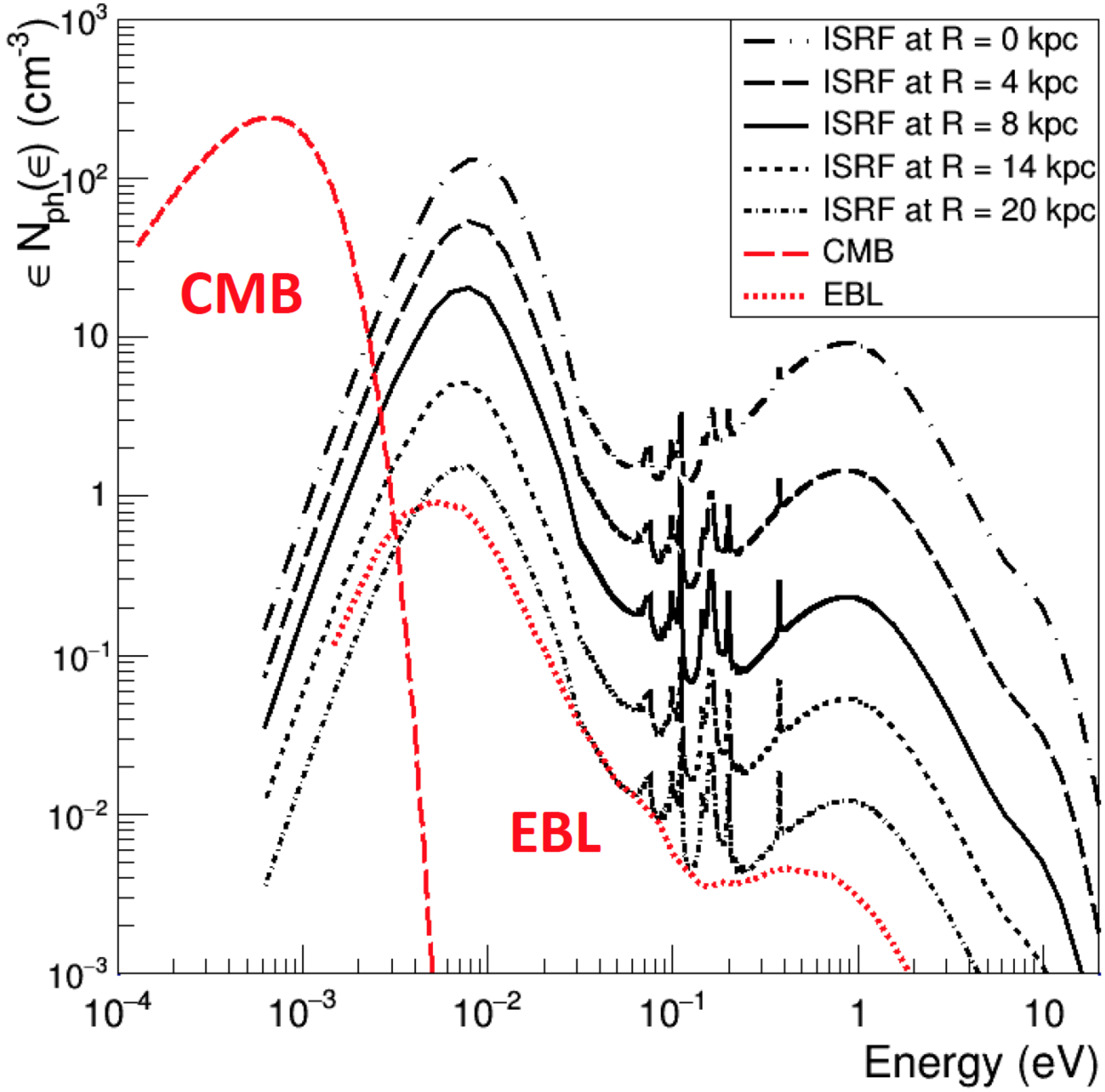
$$N_\gamma^{\rm EBL} \simeq 1.5 \text{ cm}^{-3}$$

$$N_\gamma^{\rm dust} \simeq 25 \text{ cm}^{-3}$$

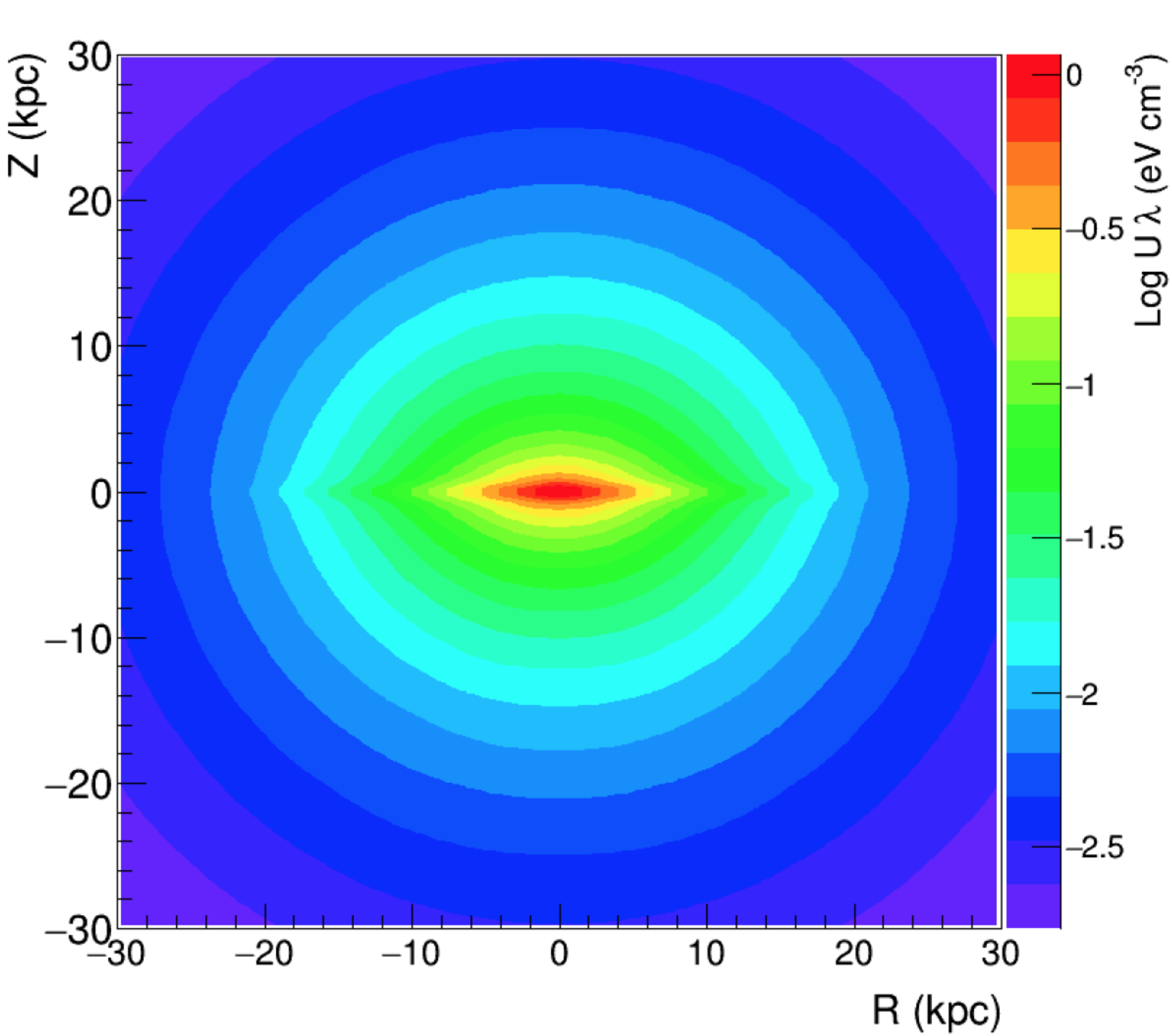
$$N_\gamma^{\rm stars} \simeq 0.43 \text{ cm}^{-3}$$

Silvia Vernetto and P.L. Phys.Rev. D (2016)

Radiation field in different points in the Galaxy

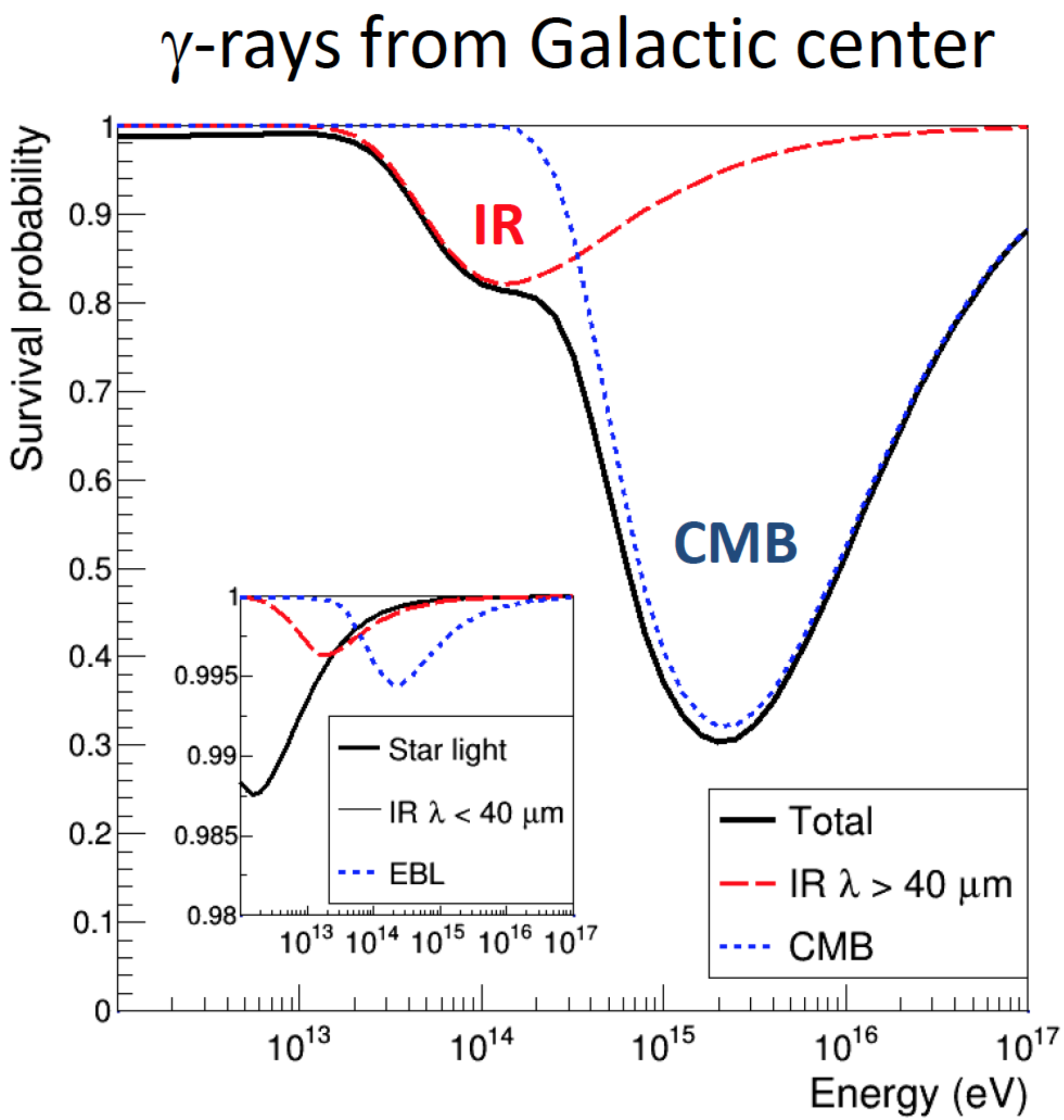


Density plot of the infrared radiation energy density in the Milky Way:



[The ISRF
(interstellar radiation field)
at infrared/optical wavelengths
is dominated by
the Galactic emission
for r < 25-30 Kpc]

Survival Probabilities for Gamma Rays



Absorption pattern has two maxima

$$E_\gamma \simeq 150 \text{ PeV}$$

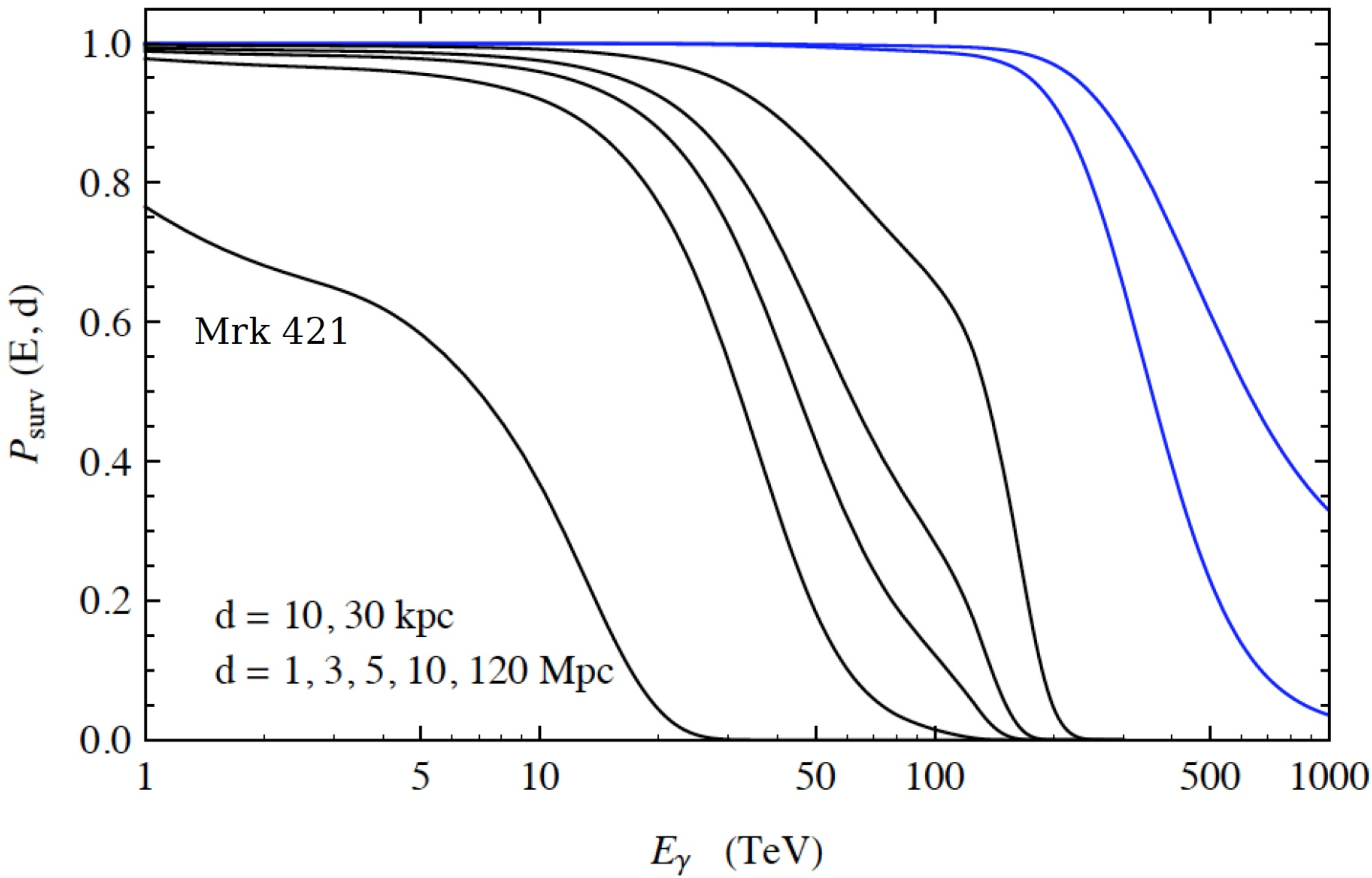
[from dust emitted radiation]

$$E_\gamma \simeq 2.2 \text{ PeV}$$

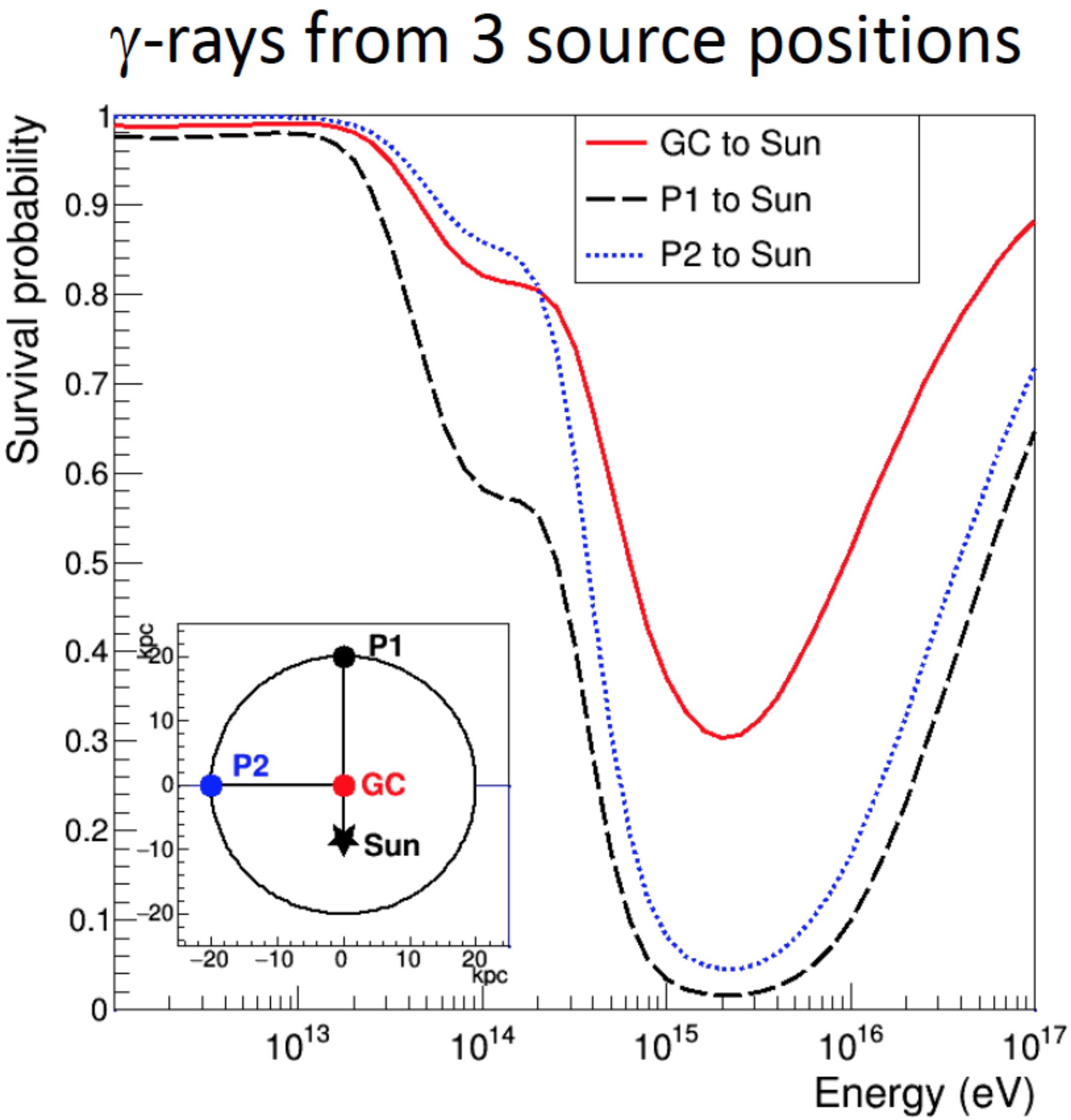
[from CMBR]

Gamma Ray absorption
(intergalactic space)

Astronomy E>100 TeV :
Galactic Astronomy



Survival Probabilities for Gamma Rays



Gamma Astronomy

$$E_\gamma \lesssim 300 \text{ TeV}$$

Possible in all Galaxy

$$P_{\text{abs}} \lesssim 0.45$$

Gamma Astronomy

$$E_\gamma \gtrsim 1 \text{ PeV}$$

Possible only in a fraction of the Galaxy

$$P_{\text{abs}} \lesssim 0.7$$

$$d \lesssim 8 \text{ kpc}$$

4. Atmospheric Neutrinos

- "Conventional flux" ($\pi^{\pm}$, K decay)
- "Prompt flux" (charm decay)

1. Muons (above few GeV) reach the ground and lose their energy before decay

$$\ell_{\mu,\mathrm{dec}} = c\,\tau_\mu\;\beta_\mu\;\frac{E_\mu}{m_\mu}$$

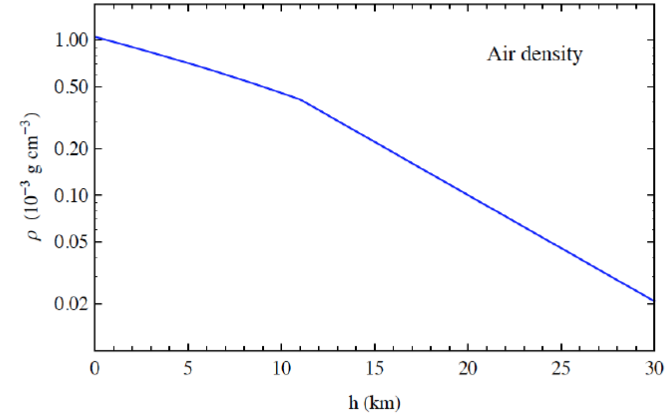
$$\simeq 6.23\;\left(\frac{E_\mu}{\mathrm{GeV}}\right)\;\mathrm{km}$$

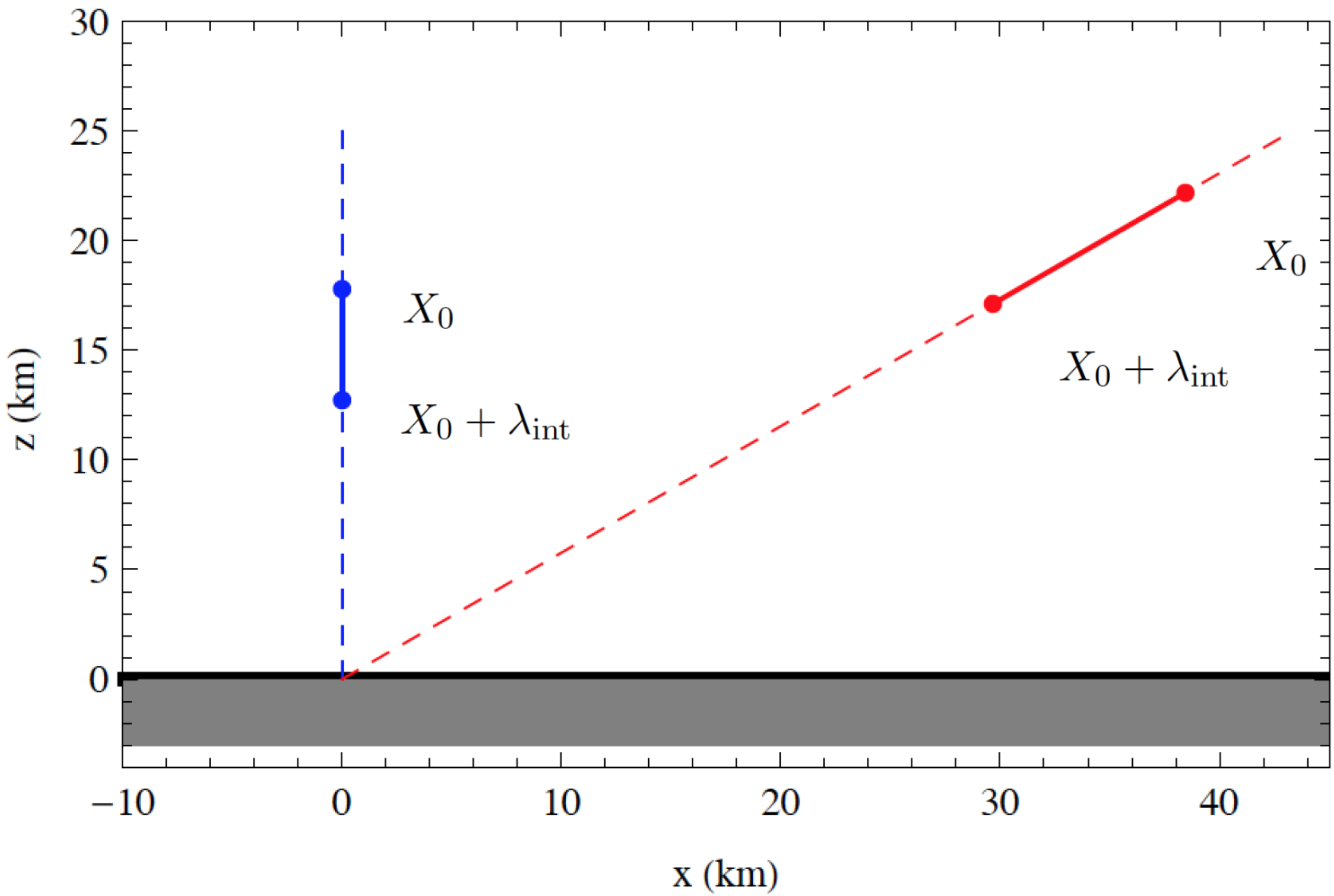
2. At high energy charged pions and kaons have decay length much longer than the interaction length:

$$\left\langle P_{\mathrm{dec}}^{\pi,K}(E,\theta_{\mathrm{z}}\right\rangle \approx \frac{\varepsilon_{\pi,K}}{E\;\cos\theta_{\mathrm{z}}}$$

Geometry of Particle Decay

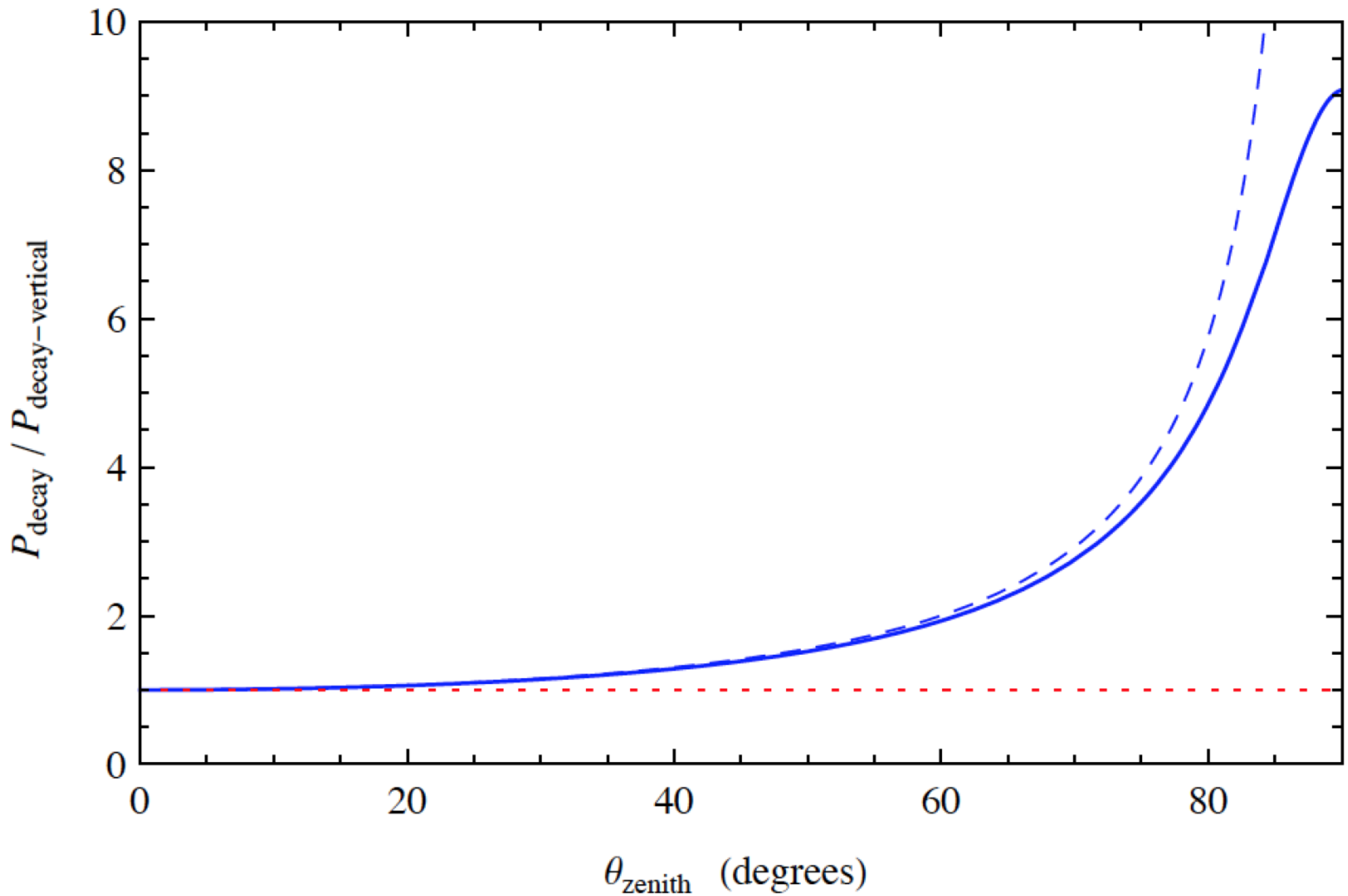
Zenith angle dependence



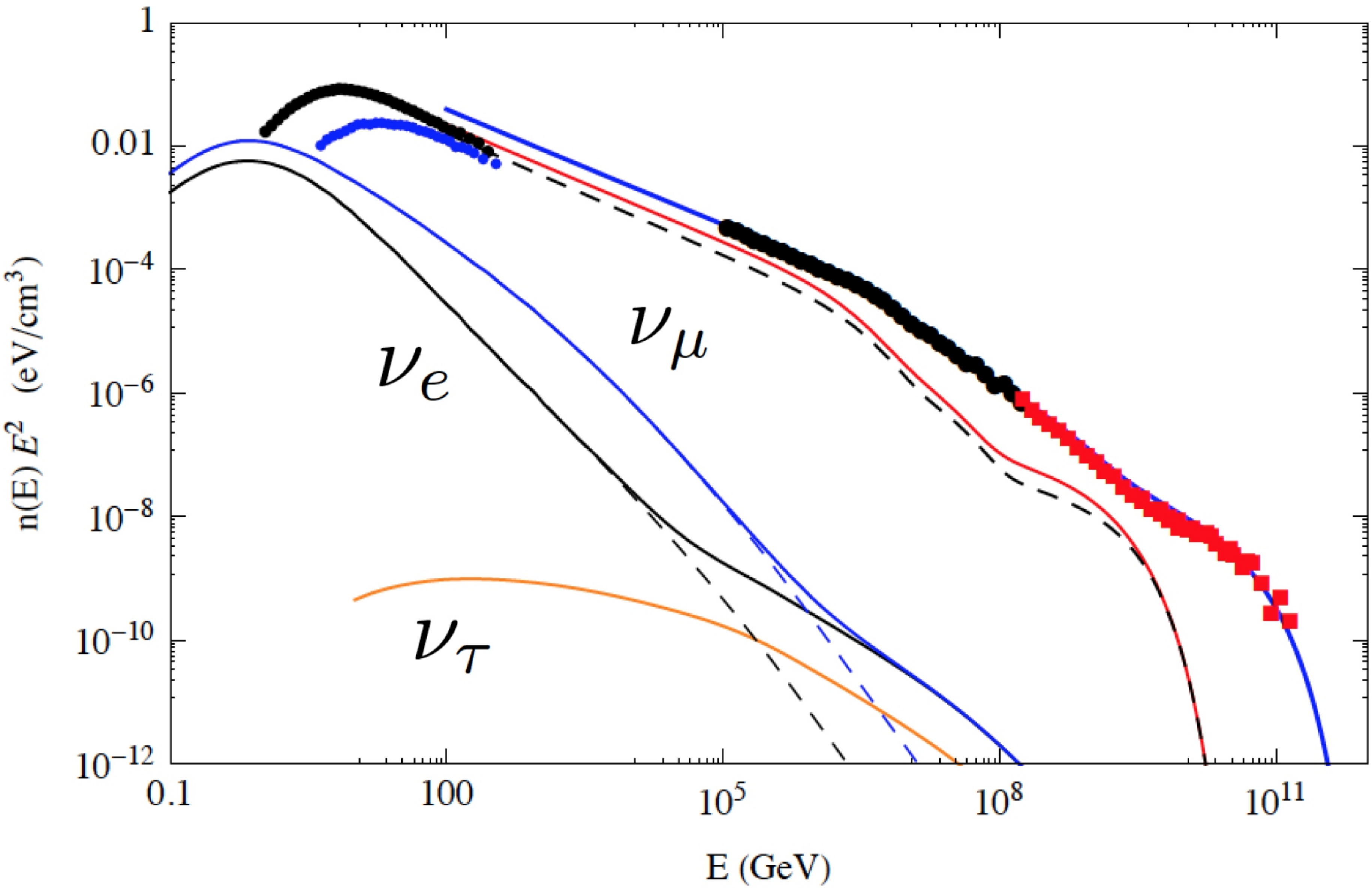


Characteristic zenith angle distribution of Standard atmospheric neutrinos

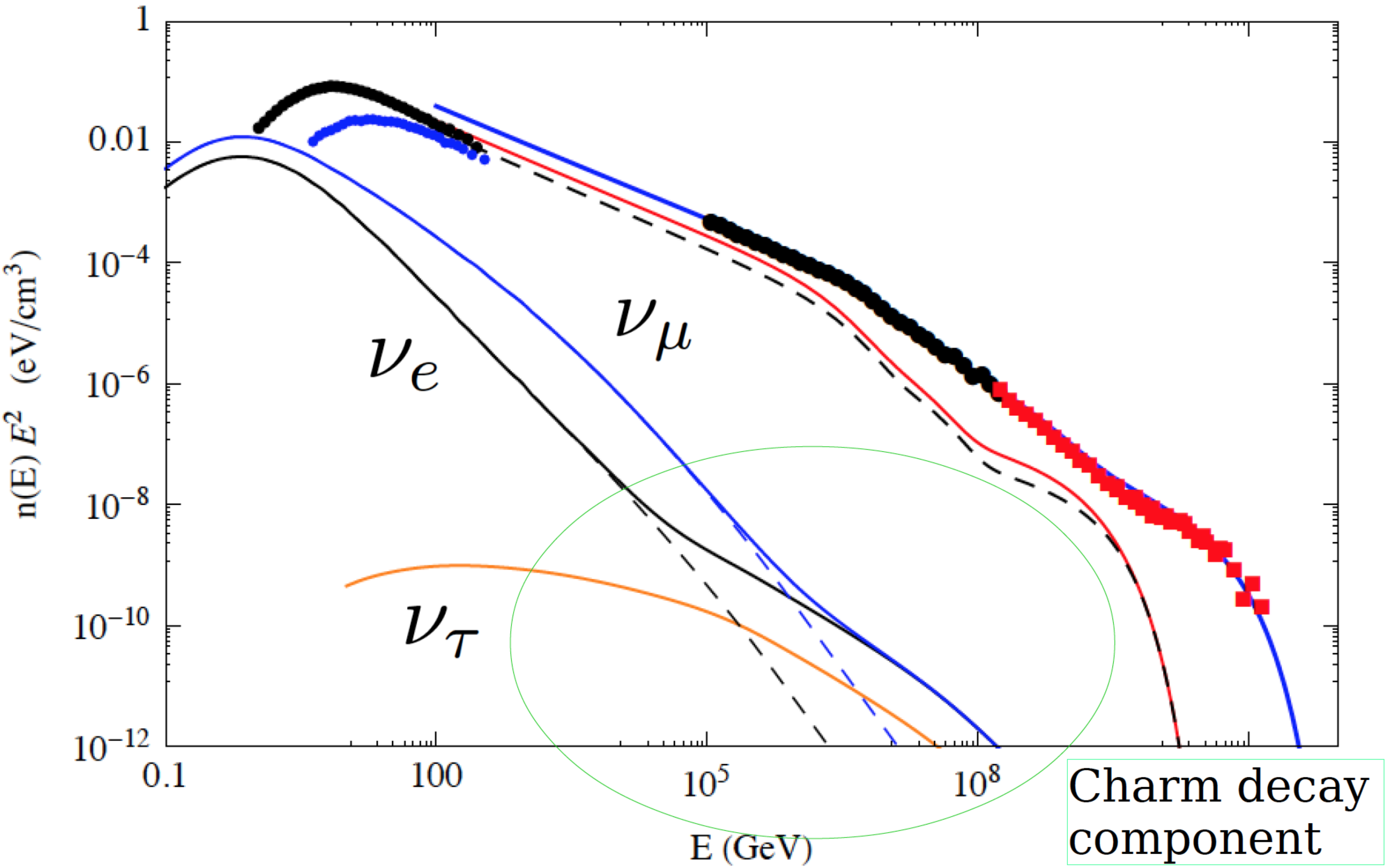
$$\phi(\theta_{\rm zenith}) \propto \frac{\langle P_{\rm dec}(\theta_{\rm zenith})\rangle}{\langle P^{\rm vert}_{\rm dec}\rangle}$$



Angle integrated Neutrino fluxes $\nu + \overline{\nu}$



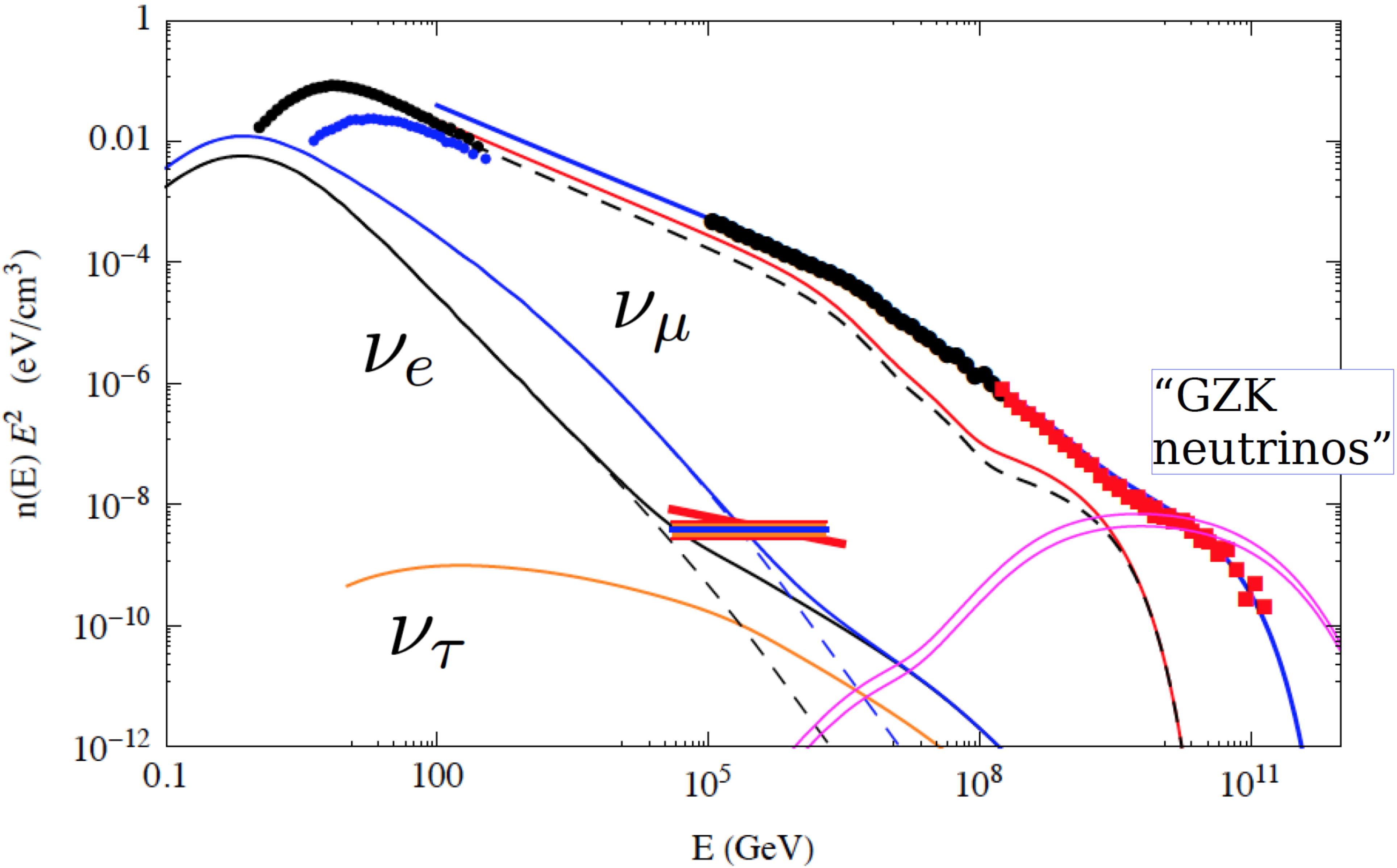
Angle integrated Neutrino fluxes

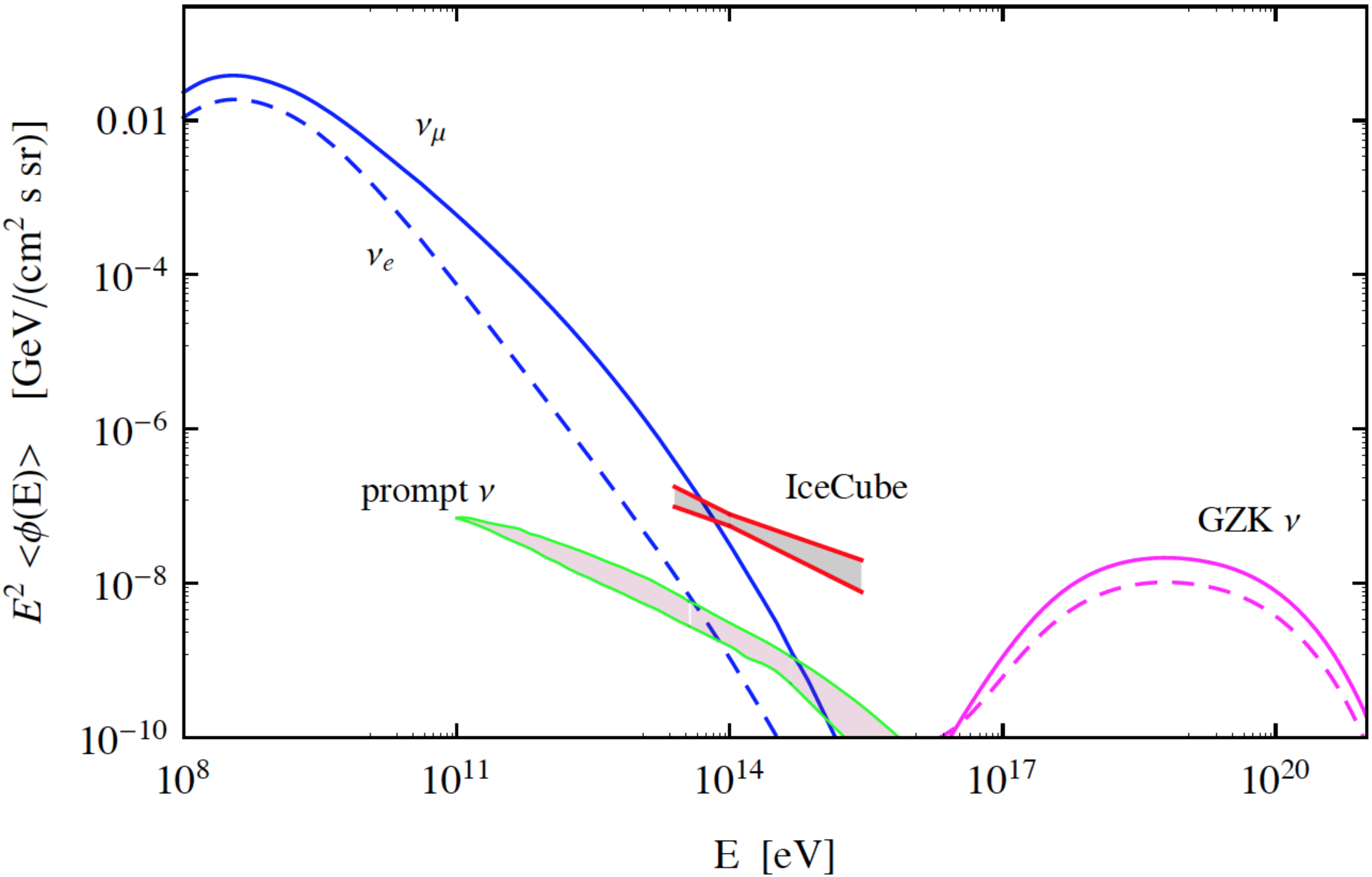


Charm decay component

Particle	$(m\ h_0)/(c\tau)$ (GeV)	B.R.	Decay Mode
π^+	114	1	$\mu^+\ \nu_\mu$
π^-	114	1	$\mu^-\ \overline{\nu}_\mu$
K^+	844	0.634	$\mu^+\ \nu_\mu$
K^+	844	0.0487	$\pi^\circ\ e^+\ \nu_e$
K^+	844	0.0327	$\pi^\circ\ \mu^+\ \nu_\mu$
K^-	844	0.634	$\mu^-\ \overline{\nu}_\mu$
K^-	844	0.0487	$\pi^\circ\ e^-\ \overline{\nu}_e$
K^-	844	0.0327	$\pi^\circ\ \mu^-\ \overline{\nu}_\mu$
K_L	203	0.194	$\pi^+\ e^-\ \nu_e \quad (\pi^-\ e^+\ \overline{\nu}_e)$
K_L	203	0.136	$\pi^+\ \mu^-\ \nu_\mu \quad (\pi^-\ \mu^+\ \overline{\nu}_\mu)$
D^+	3.8×10^7	0.172	$e^+\ \nu_e\ X \quad (\mu^+\ \nu_\mu\ X)$
D^-	3.8×10^7	0.172	$e^-\ \overline{\nu}_e\ X \quad (\mu^-\ \overline{\nu}_\mu\ X)$
D^0	9.6×10^7	0.0687	$e^+\ \nu_e\ X \quad (\mu^+\ \nu_\mu\ X)$
$\overline{D}^0$	9.6×10^7	0.0687	$e^-\ \overline{\nu}_e\ X \quad (\mu^-\ \overline{\nu}_\mu\ X)$
Λ_c	2.4×10^8	0.045	$e^+\ \overline{\nu}_e\ X \quad (\mu^+\ \nu_\mu\ X)$
D_s^+	8.5×10^7	0.064	$\tau^+\ \nu_\tau$
D_s^-	8.5×10^7	0.064	$\tau^-\ \overline{\nu}_\tau$

IceCube fit of the “extraterrestrial component”
(per each flavor)





E^2 <ϕ(E)> [GeV/(cm^2 s sr)]
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^{11}
10^{14}
10^{17}
10^{20}
E [eV]
ν_μ
ν_e
prompt ν
IceCube
GZK ν

Flavor Content

[flux ratios]

	Atmospheric "Standard"	Atmospheric "Prompt"	Astrophysical $(p\text{–gas})$	Astrophysical $(p\text{–}\gamma)$
$\nu_e + \overline{\nu}_e$	1	1	1	1
$\nu_\mu + \overline{\nu}_\mu$	40	1	1	1
$\nu_\tau + \overline{\nu}_\tau$	~ 0	0.1	1	1
$\mu^+ + \mu^-$	130	0.85	–	–
γ/ν	–	–	1	1.5

Flavor Content

	Atmospheric "Standard"	Atmospheric "Prompt"	Astrophysical (p–gas)	Astrophysical (p–γ)
$\nu_e + \overline{\nu}_e$	1	1	1	1
$\nu_\mu + \overline{\nu}_\mu$	40	1	1	1
$\nu_\tau + \overline{\nu}_\tau$	~ 0	0.1	1	1
$\mu^+ + \mu^-$	130	0.85	–	–
γ/ν	–	–	1	1.5

1. More ν_μ than ν_e — 2-body decay of pion/kaon
2. Absence of ν_τ — Decay forbidden (tau mass)
3. More μ than ν_μ — Kinematics of pion decay

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$$

Charged Pions decay into muon-neutrinos

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

$$\mu^- \to \nu_\mu + \overline{\nu}_e + e^-$$

Electron neutrinos generated by 3-body decays of kaons.

[2-body decay V-A structure of the interaction]

$$\frac{\Gamma(\pi^+ \to e^+ + \nu_e)}{\Gamma(\pi^+ \to \mu^+ + \nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28 \times 10^{-4}$$

Flavor Content

	Atmospheric "Standard"	Atmospheric "Prompt"	Astrophysical	
			(p–gas)	(p–γ)
$\nu_e + \overline{\nu}_e$	1	1	1	1
$\nu_\mu + \overline{\nu}_\mu$	40	1	1	1
$\nu_\tau + \overline{\nu}_\tau$	~ 0	0.1	1	1
$\mu^+ + \mu^-$	130	0.85	–	–
γ/ν	–	–	1	1.5

1. Equal ν_μ and ν_e — Universality
2. Small (10%) ν_τ — 2 body decay of Ds
3. slightly less μ than ν_μ — Kinematics of charm decay

Flavor Content

	Atmospheric "Standard"	Atmospheric "Prompt"	Astrophysical $(p\text{–gas})$	$(p\text{–}\gamma)$
$\nu_e + \overline{\nu}_e$	1	1	1	1
$\nu_\mu + \overline{\nu}_\mu$	40	1	1	1
$\nu_\tau + \overline{\nu}_\tau$	~ 0	0.1	1	1
$\mu^+ + \mu^-$	130	0.85	–	
γ/ν	–	–	1	1.5

1. Equal ν_μ ν_e and ν_τ

Flavor Content

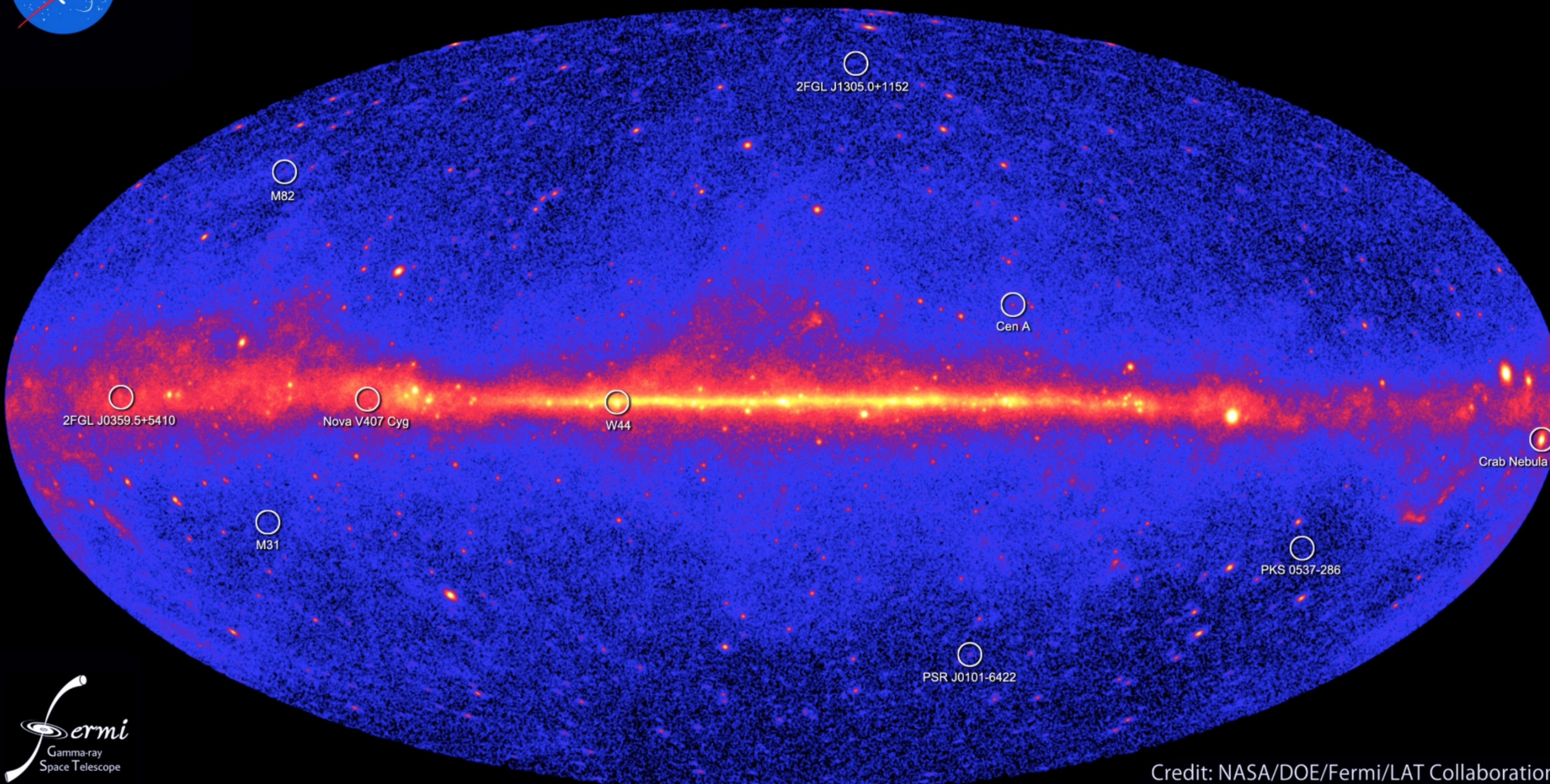
	Atmospheric "Standard"	Atmospheric "Prompt"	Astrophysical (p–gas)	Astrophysical (p–γ)
$\nu_e + \overline{\nu}_e$	1	1	1	1
$\nu_\mu + \overline{\nu}_\mu$	40	1	1	1
$\nu_\tau + \overline{\nu}_\tau$	~ 0	0.1	1	1
$\mu^+ + \mu^-$	130	0.85	–	1.5
γ/ν	–	–	1	

In principle key role for ν_τ

5. The Gamma Ray sky

- Diffuse Galactic Flux
- Galactic Sources
- Extragalactic Sources

Fermi two-year all-sky map



Credit: NASA/DOE/Fermi/LAT Collaboration

1. Ensemble of (quasi)-point sources

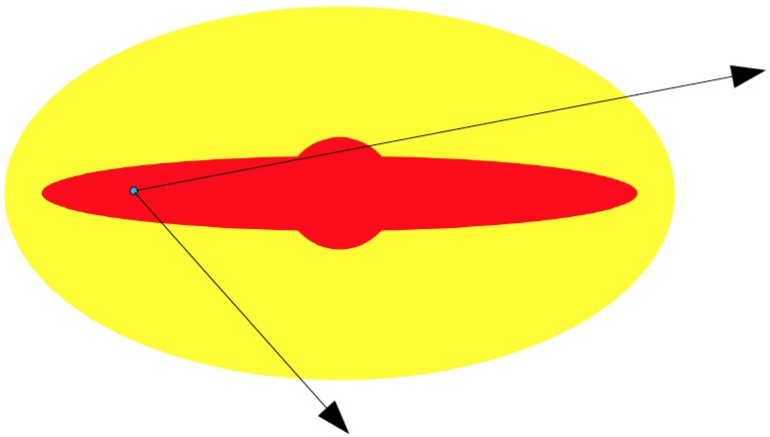
2. Diffuse Galactic Flux

(generated by cosmic rays magnetically confined in the Milky Way)

3. Isotropic flux.

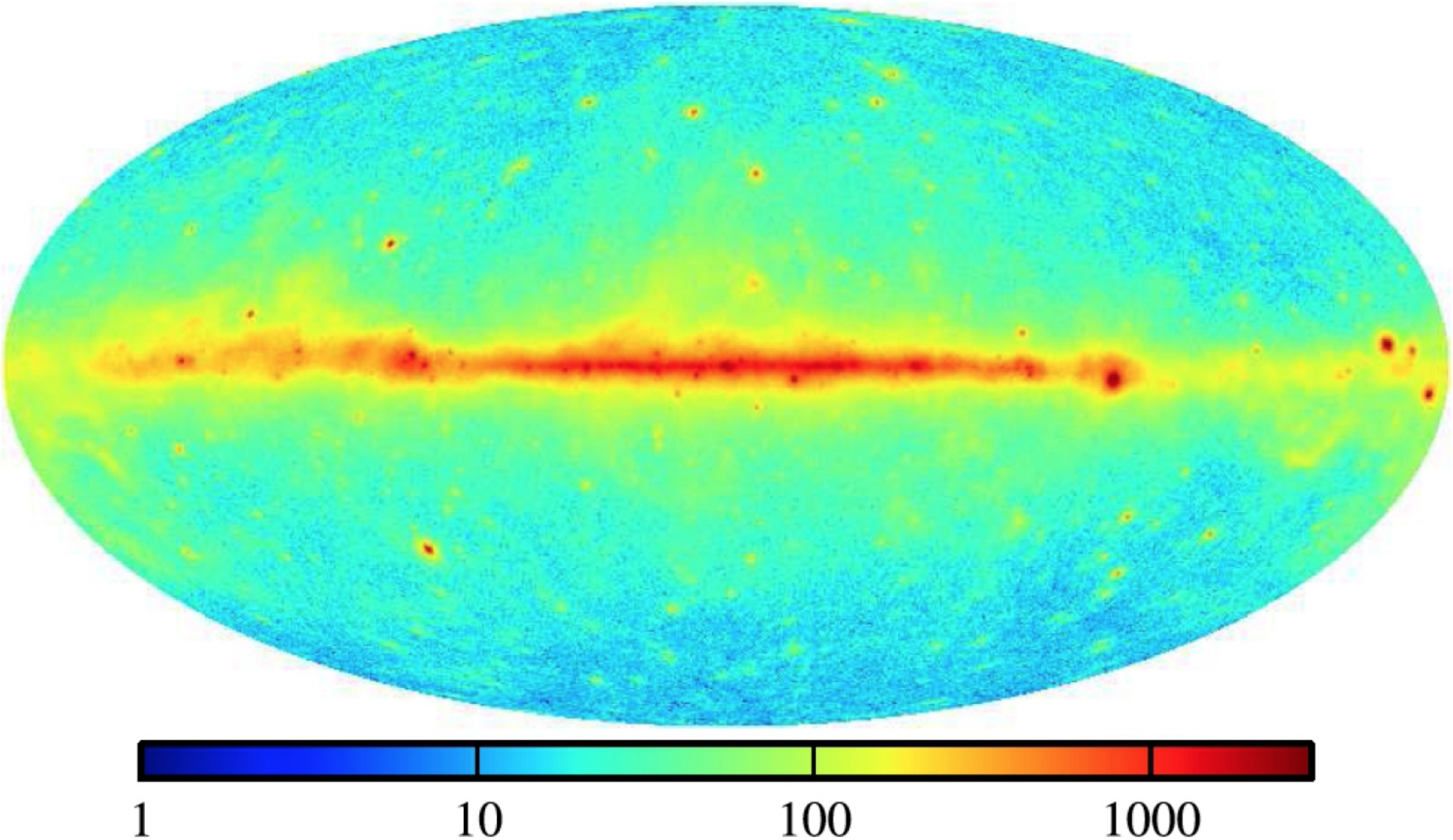
(attributed to an ensemble of unresolved extragalactic sources)

Diffuse Emission



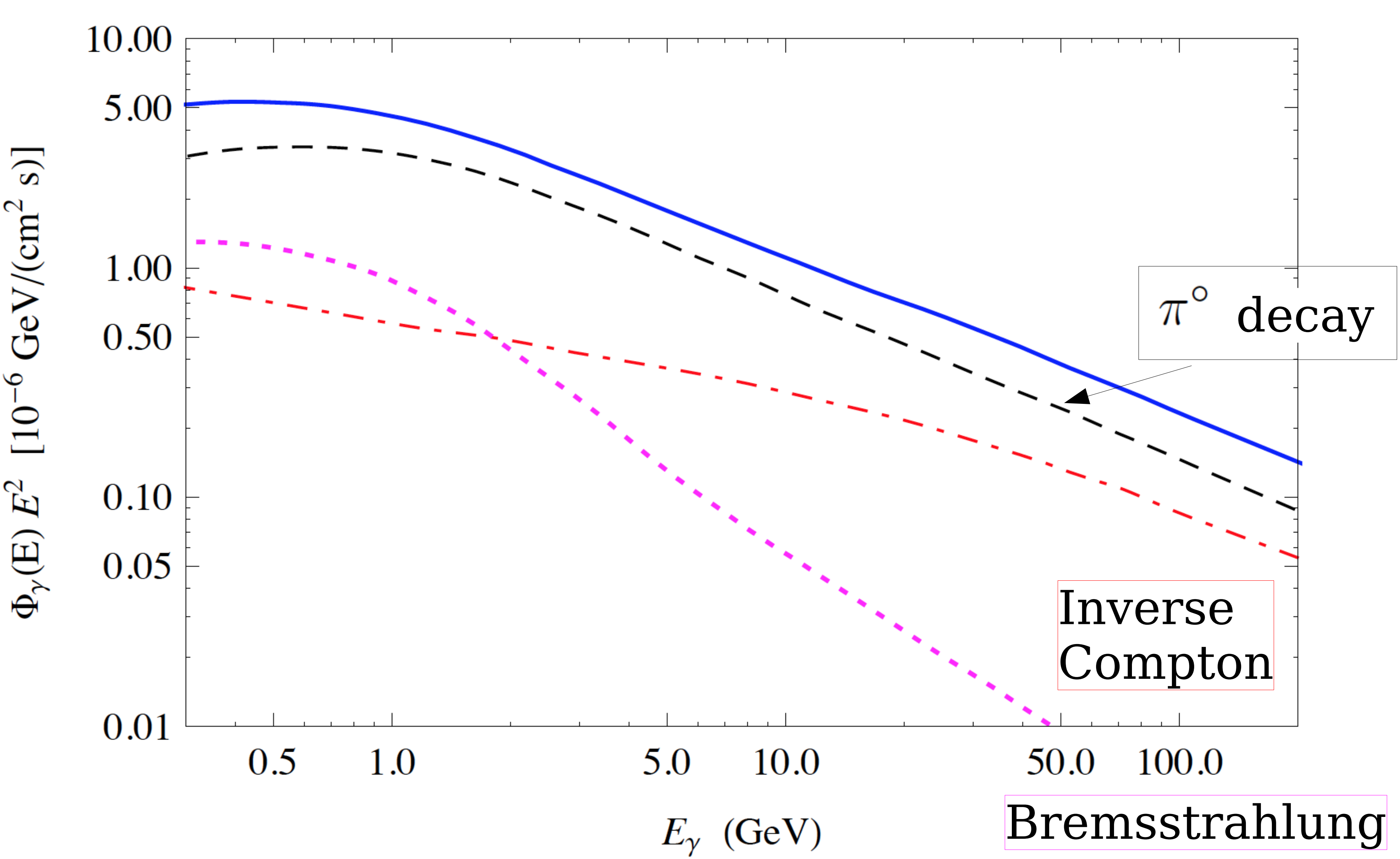
Fermi–LAT counts

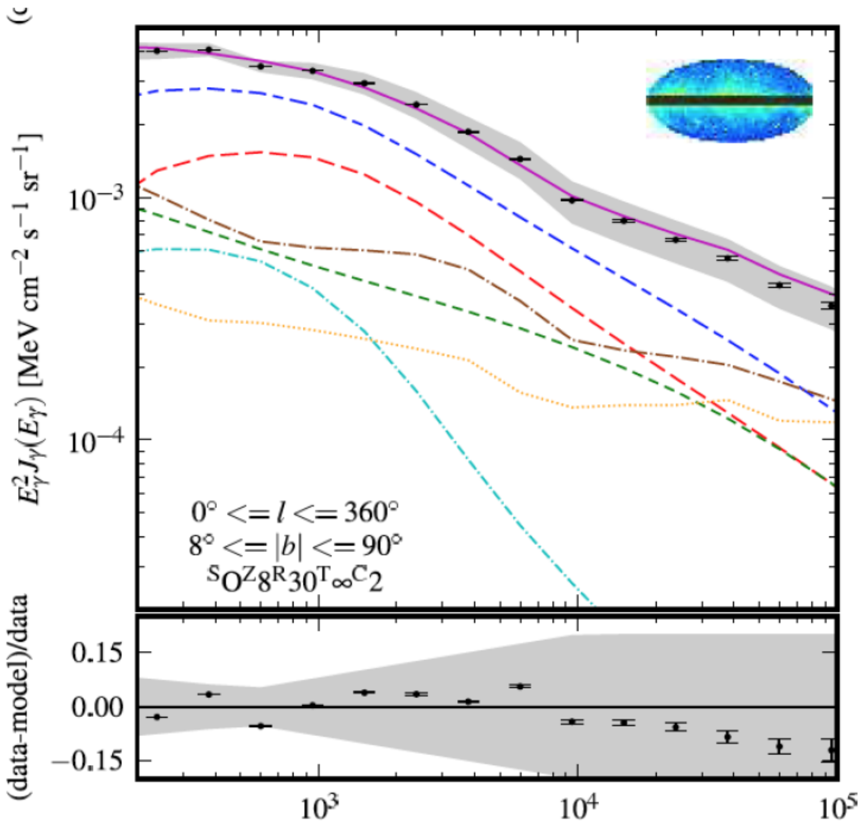
Galactic coordinates

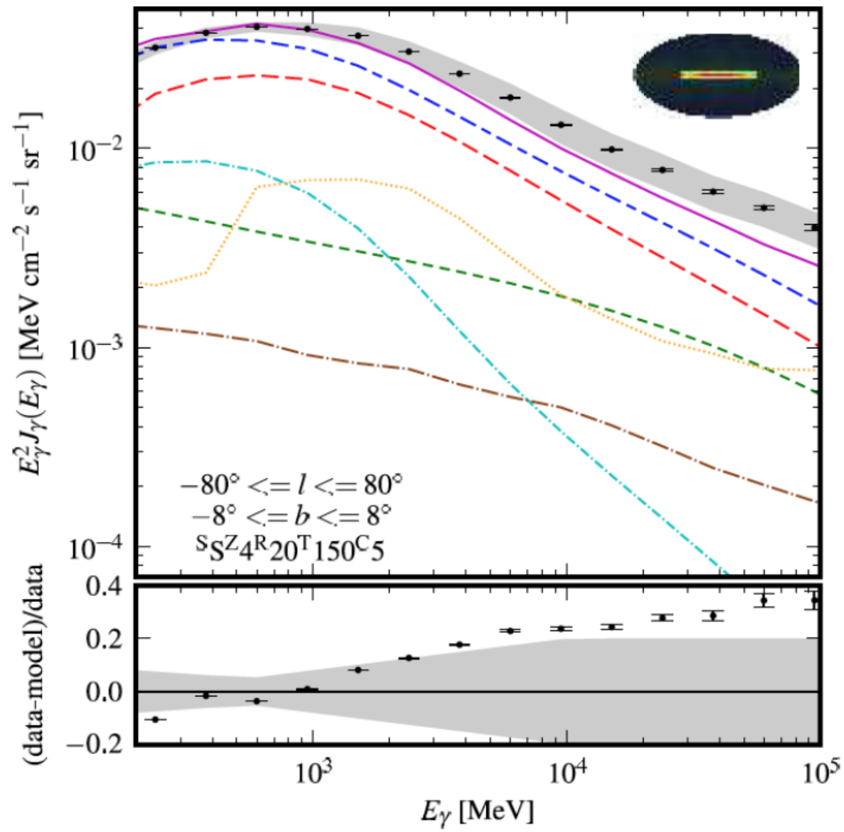


energy range 200 MeV to 100 GeV

Decomposition of the diffuse Galactic flux







$$p + p_{\text{i.s.m.}} \to \pi^\circ + \ldots$$

$$\pi^\circ \to \gamma + \gamma$$

Description reasonably successful.
[but several ambiguities and open problems remain.]

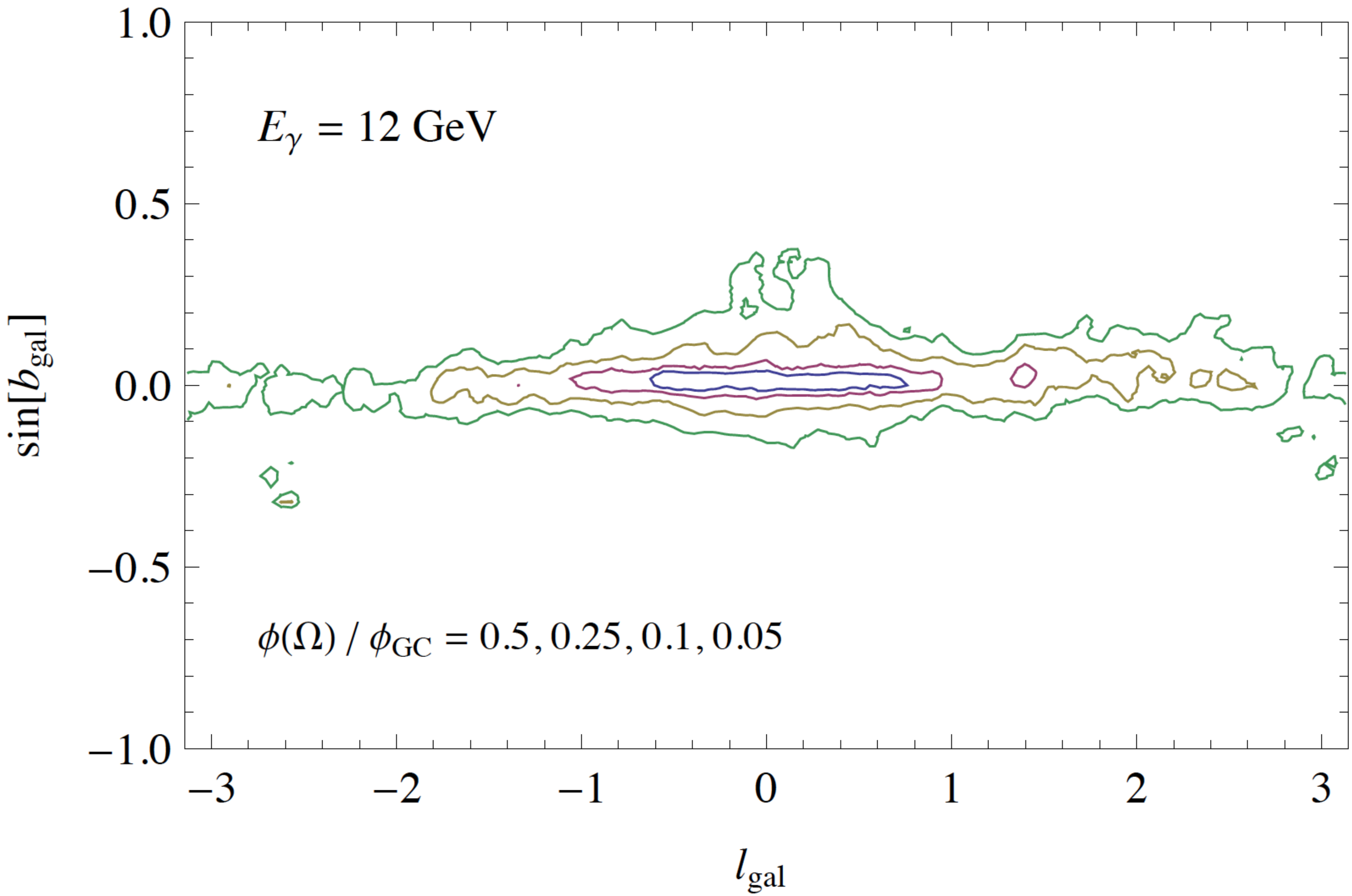
Inverse Compton

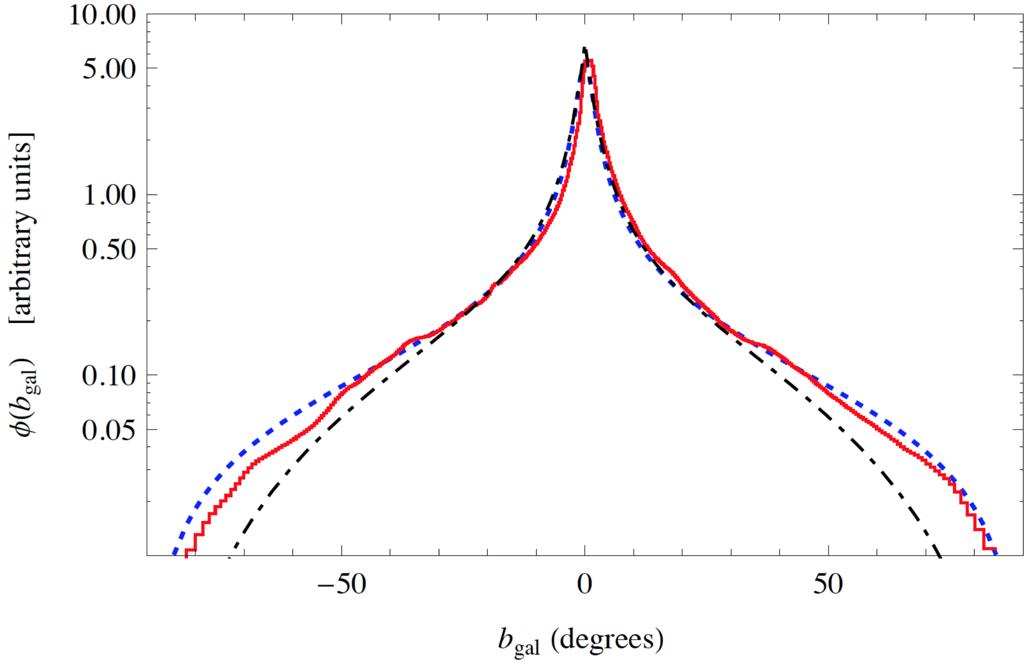
$$e^\pm + Z \to e^\pm + \gamma + Z$$

Bremsstrahlung

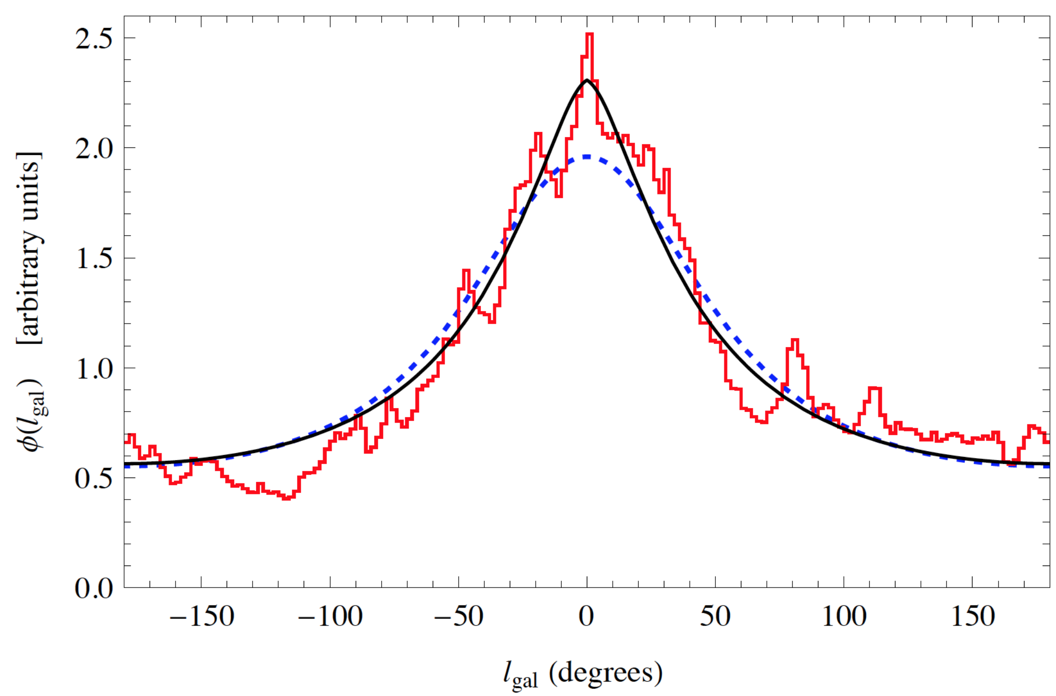
$$e^\pm + Z \to e^\pm + \gamma + Z$$

Angular distribution of the diffuse Galactic emission





10.00
5.00
1.00
0.50
0.10
0.05
−50
0
50
$\phi(b_{\rm gal})$ [arbitrary units]
$b_{\rm gal}$ (degrees)

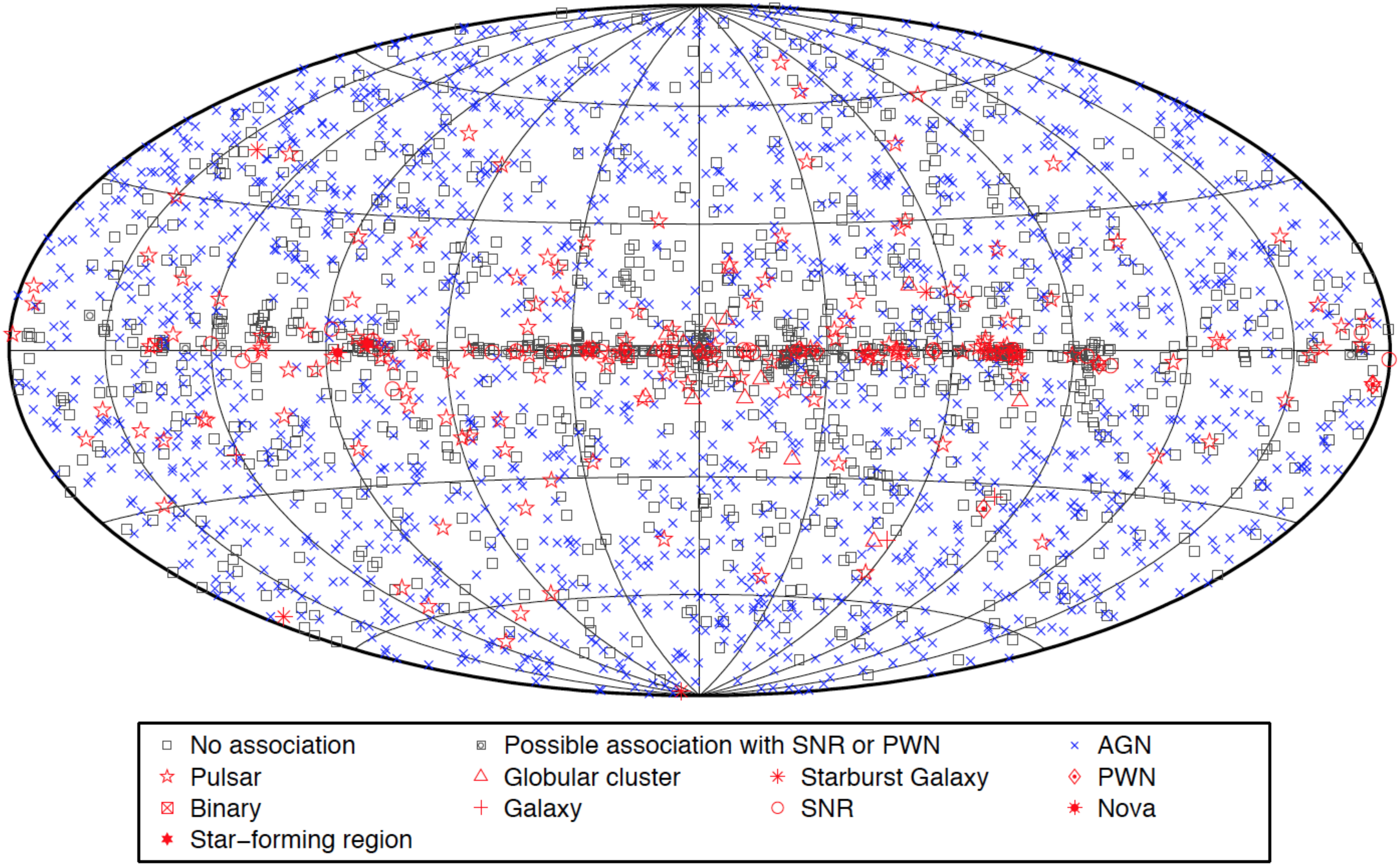


2.5
2.0
1.5
1.0
0.5
0.0
−150
−100
−50
0
50
100
150
$\phi(l_{\rm gal})$ [arbitrary units]
$l_{\rm gal}$ (degrees)

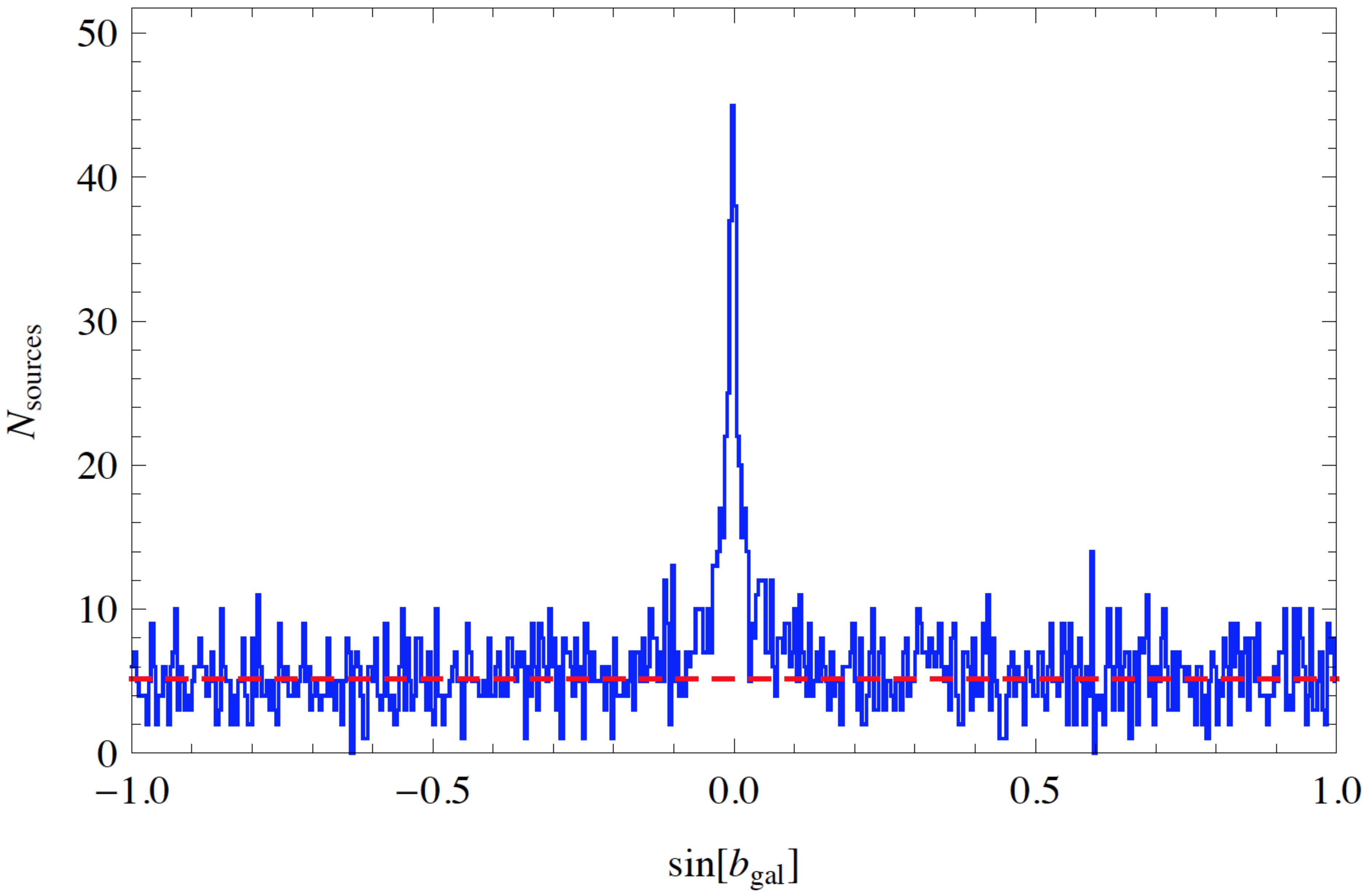
3rd FERMI Catalog

3034 sources

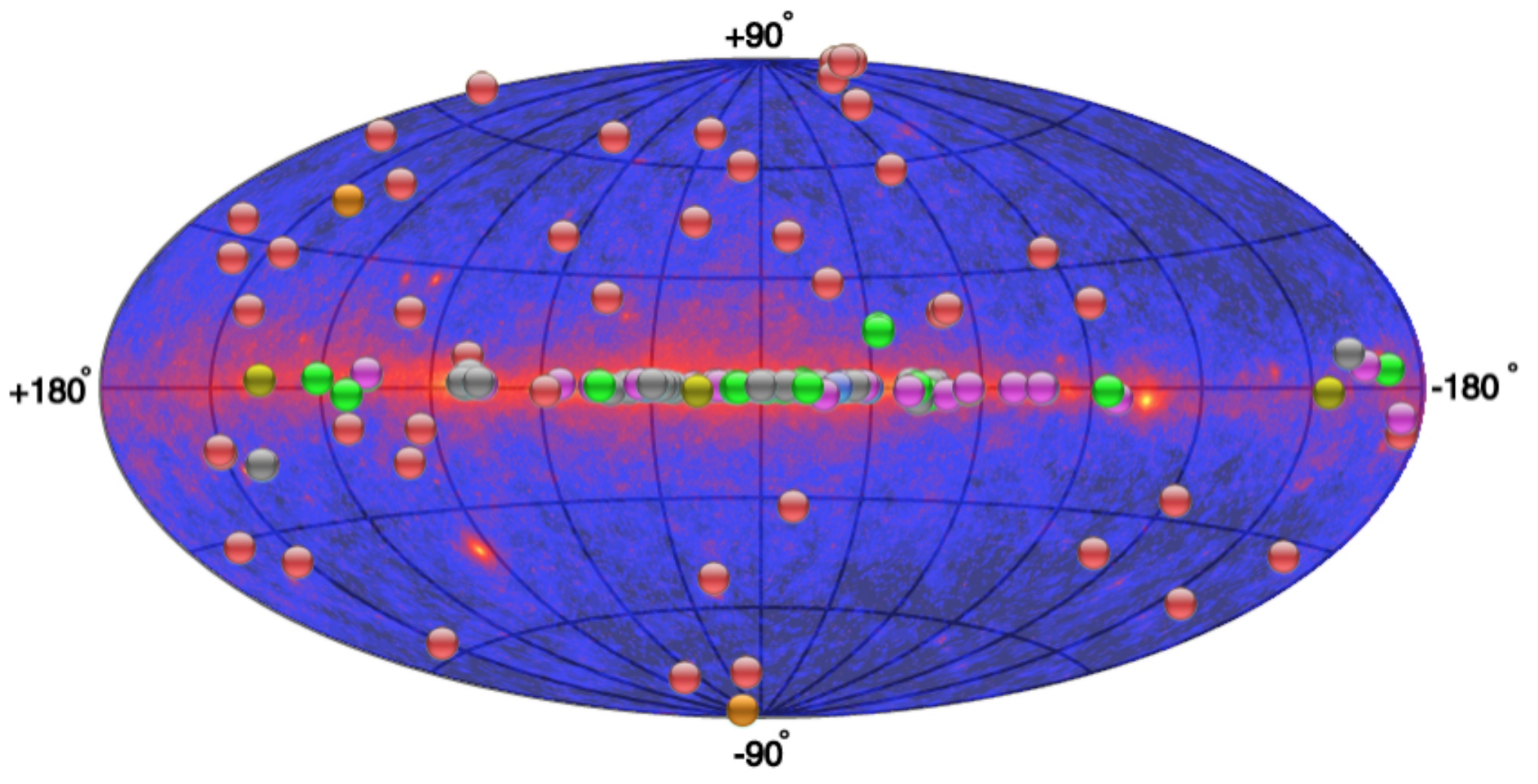
E > 100 MeV



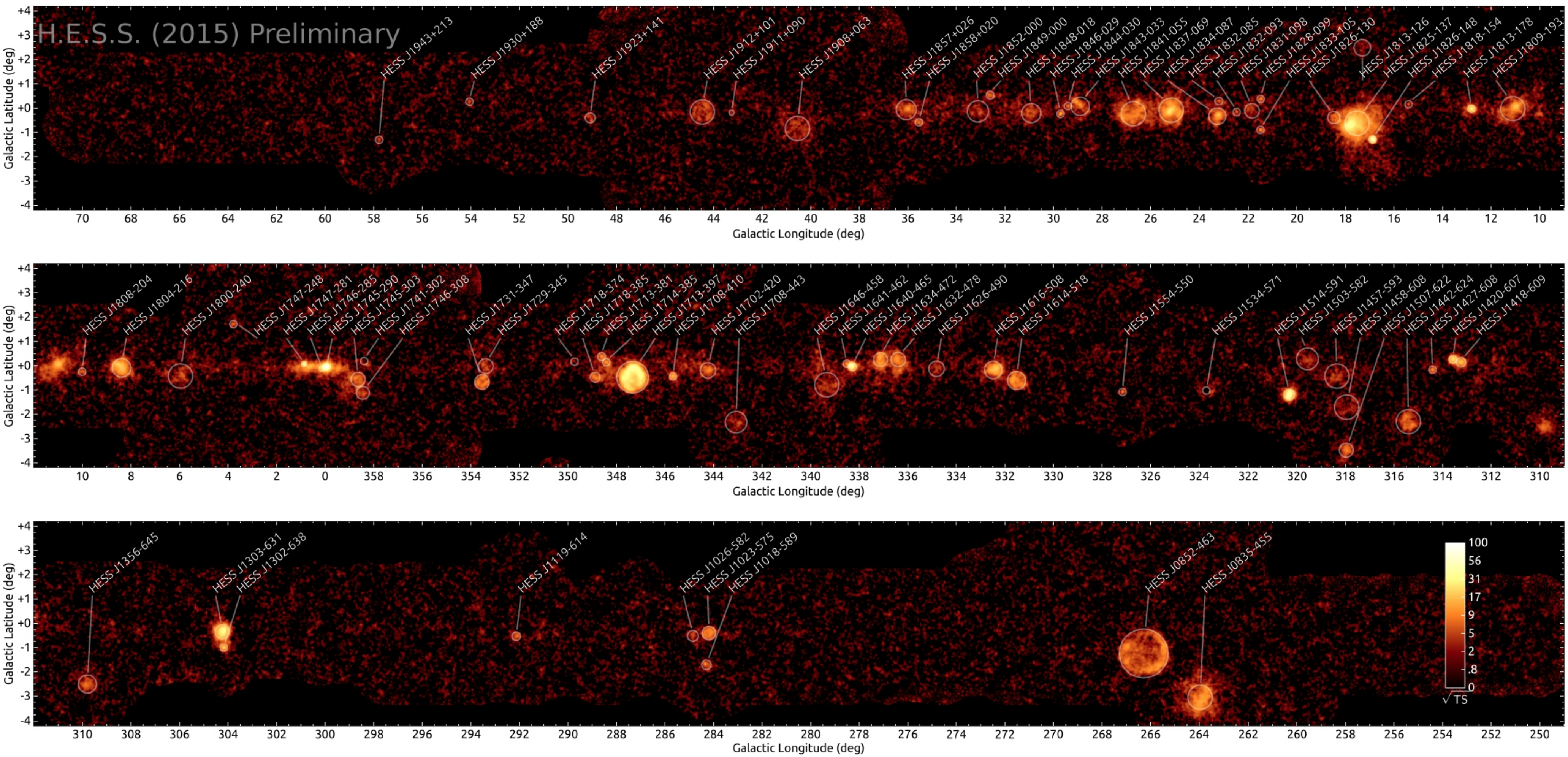
3034 3rd catalog sources [approximately 440 are galactic]



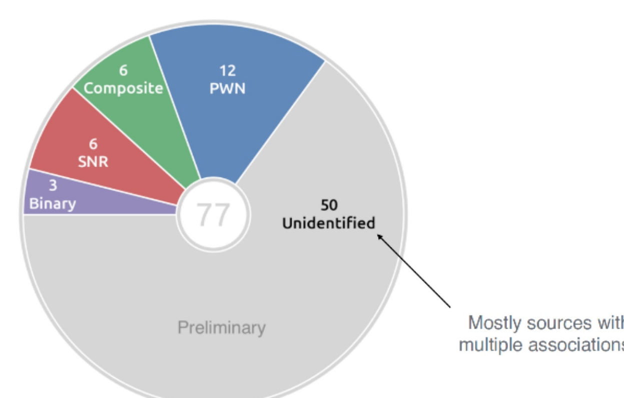
TeV Sky 170 → 200 Sources



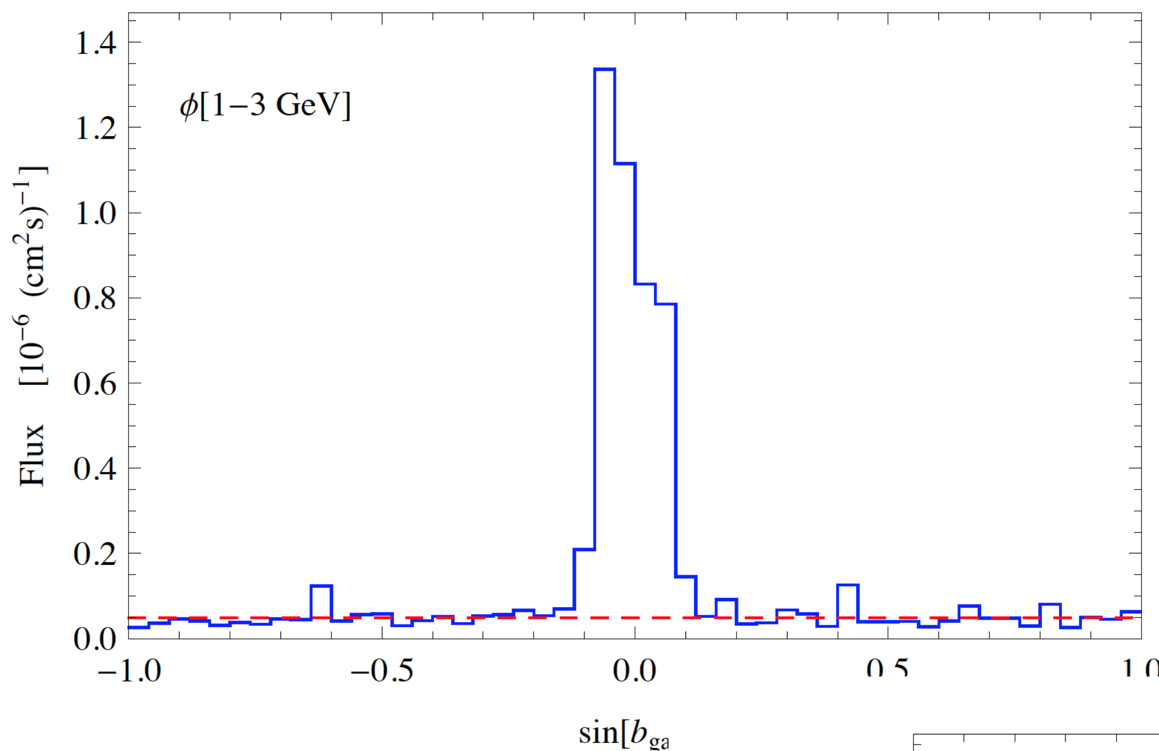
blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky



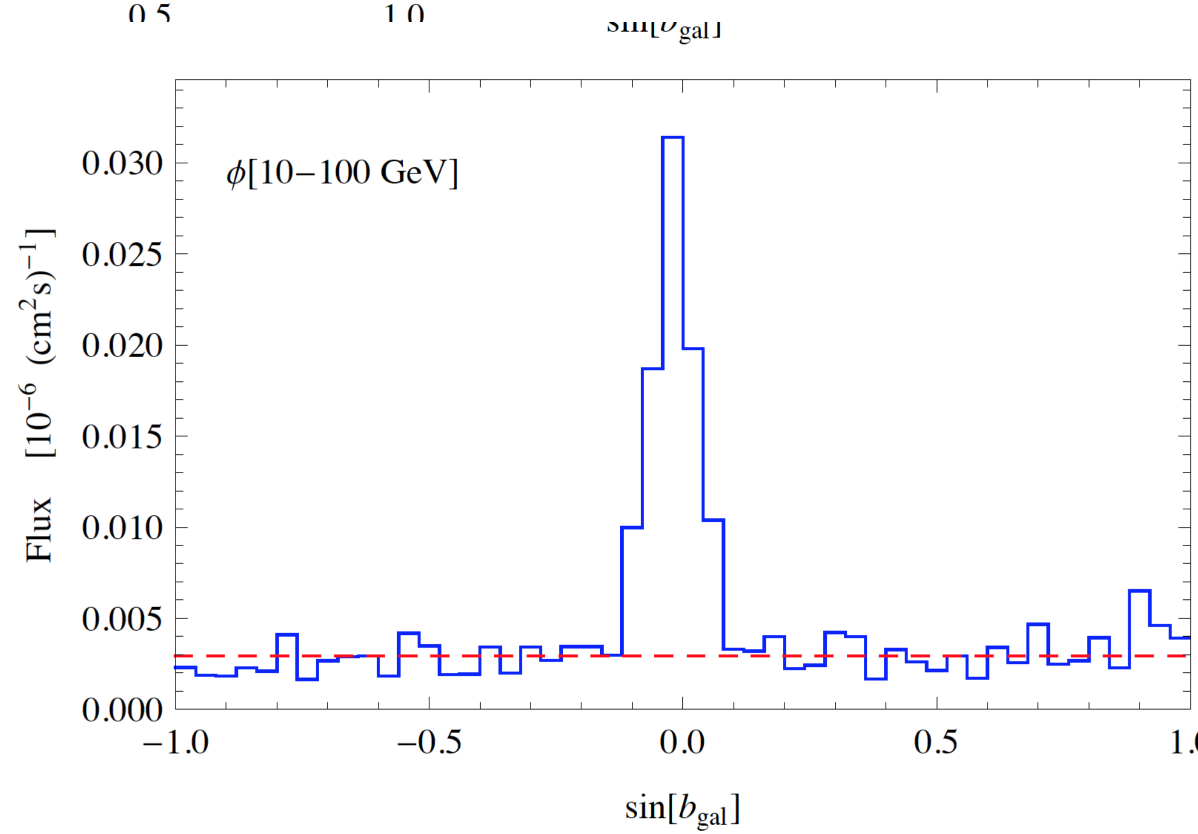
Firm identifications



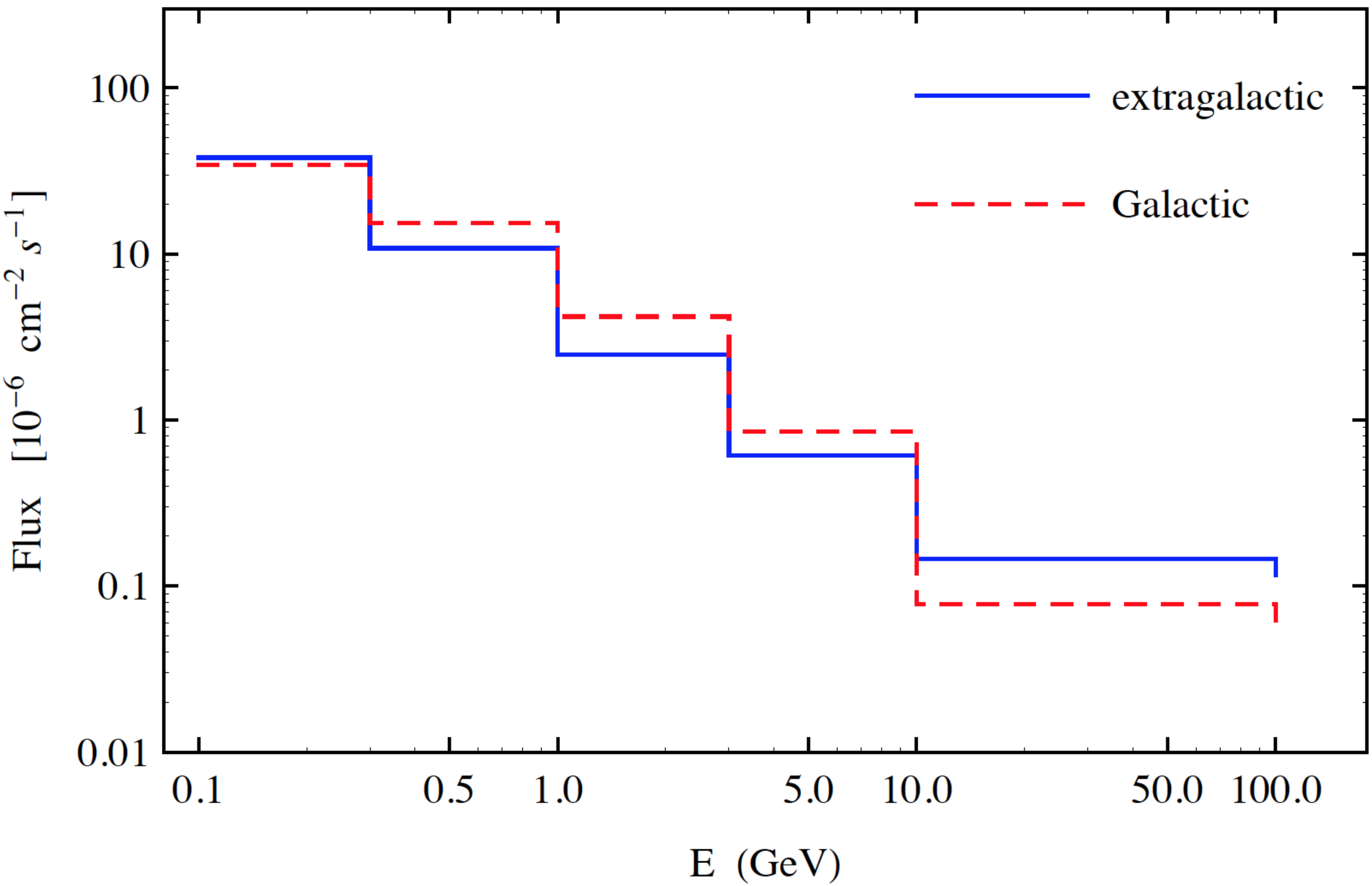
HESS survey of Galactic Plane [ICRC 2015] 77 “firm identifications”



ϕ[1–3 GeV]
Flux [10^{-6} (cm^{2}s)$^{-1}$]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0
sin[b_{ga}

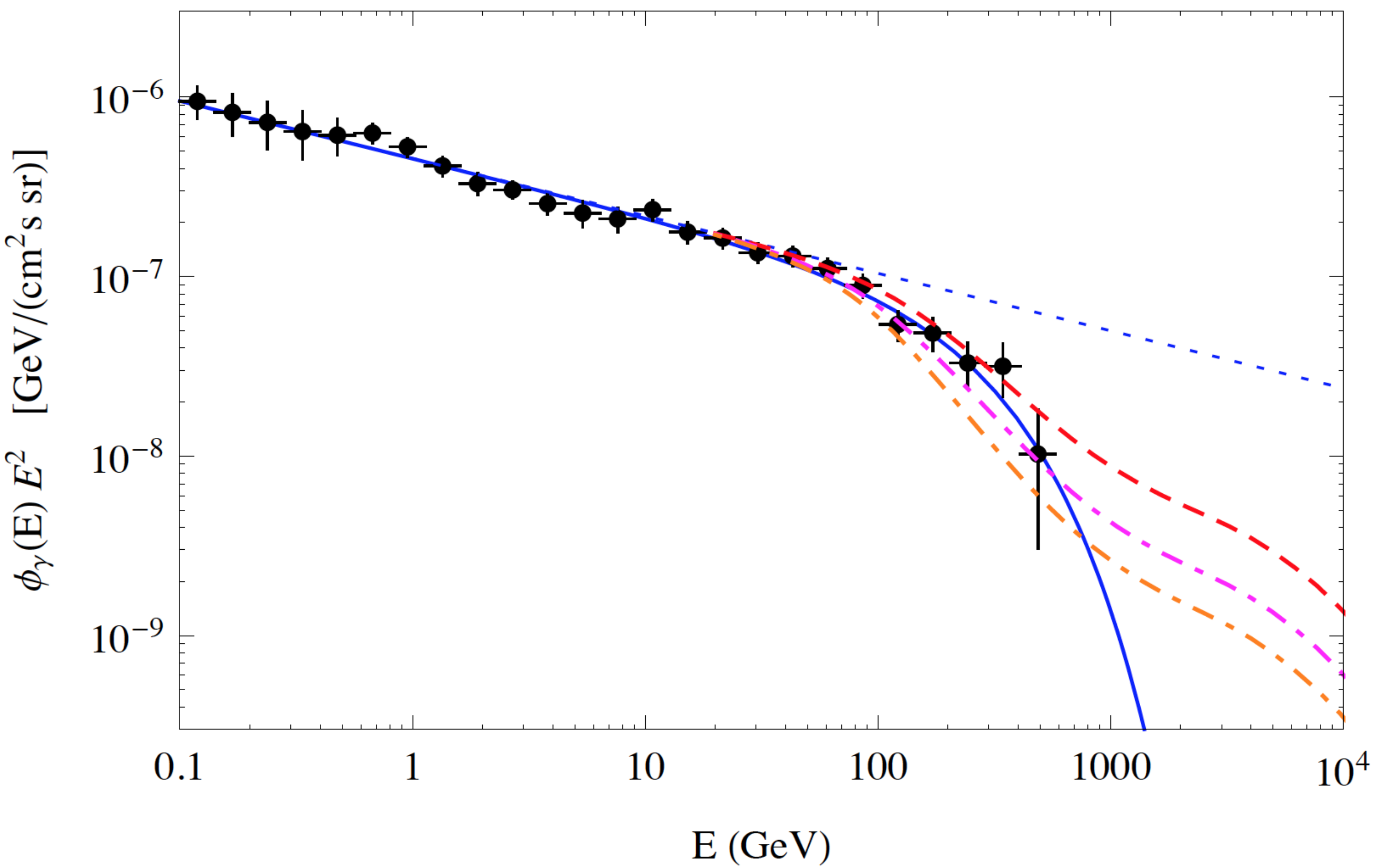


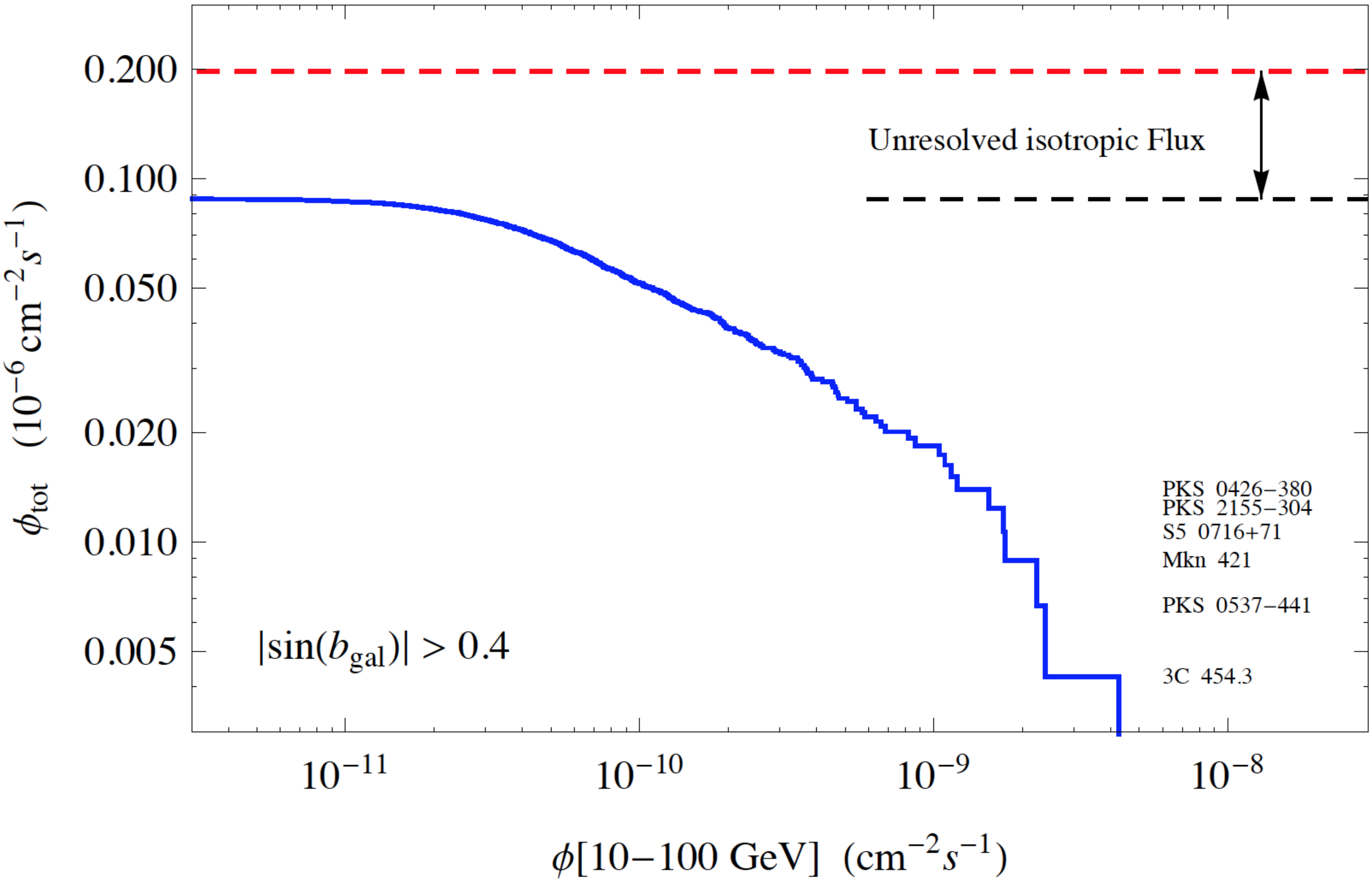
ϕ[10–100 GeV]
Flux [10^{-6} (cm^{2}s)$^{-1}$]
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−1.0
−0.5
0.0
0.5
1.0
sin[b_{gal}]



extragalactic
Galactic
Flux [10^{-6} cm^{-2} s^{-1}]
100
10
1
0.1
0.01
0.1
0.5
1.0
5.0
10.0
50.0
100.0
E (GeV)

Isotropic (extragalactic) flux





0.200
0.100
0.050
0.020
0.010
0.005
ϕ_{tot} $(10^{-6}\,\mathrm{cm}^{-2}s^{-1})$
Unresolved isotropic Flux
PKS 0426−380
PKS 2155−304
S5 0716+71
Mkn 421
PKS 0537−441
3C 454.3
$|\sin(b_{gal})| > 0.4$
10^{-11}
10^{-10}
10^{-9}
10^{-8}
$\phi[10{-}100\ \mathrm{GeV}]$ $(\mathrm{cm}^{-2}s^{-1})$

Gamma Rays in [1-100 GeV] energy interval.

$$\Phi_{\rm sources}^{\rm poles} = \sum_j \phi_j = 1.92 \times 10^{-6}\ {\rm cm}^{-2}\,{\rm s}^{-1}$$

Resolved flux

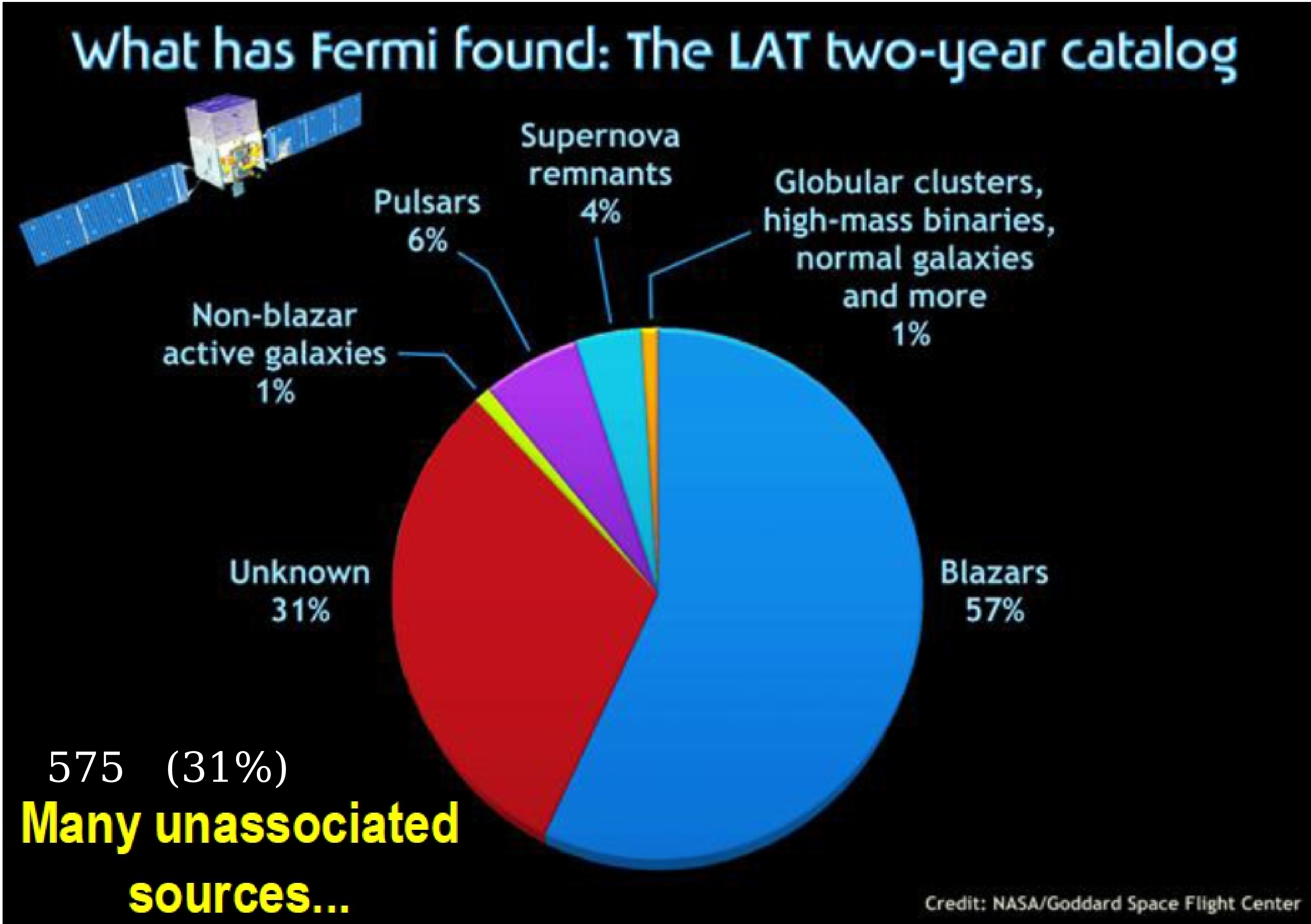
$$\phi_{\rm iso}\ \Delta\Omega = 1.63 \times 10^{-6}\ {\rm cm}^{-2}\,{\rm s}^{-1}$$

Unresolved flux

$$\Phi_{\rm extra} \simeq \frac{4\pi}{\Delta\Omega}\ \Phi_{\rm sources}^{\rm poles} + 4\pi\ \phi_{\rm iso}$$

$$\simeq 5.5 \times 10^{-6}\ {\rm cm}^{-2}\,{\rm s}^{-1}$$

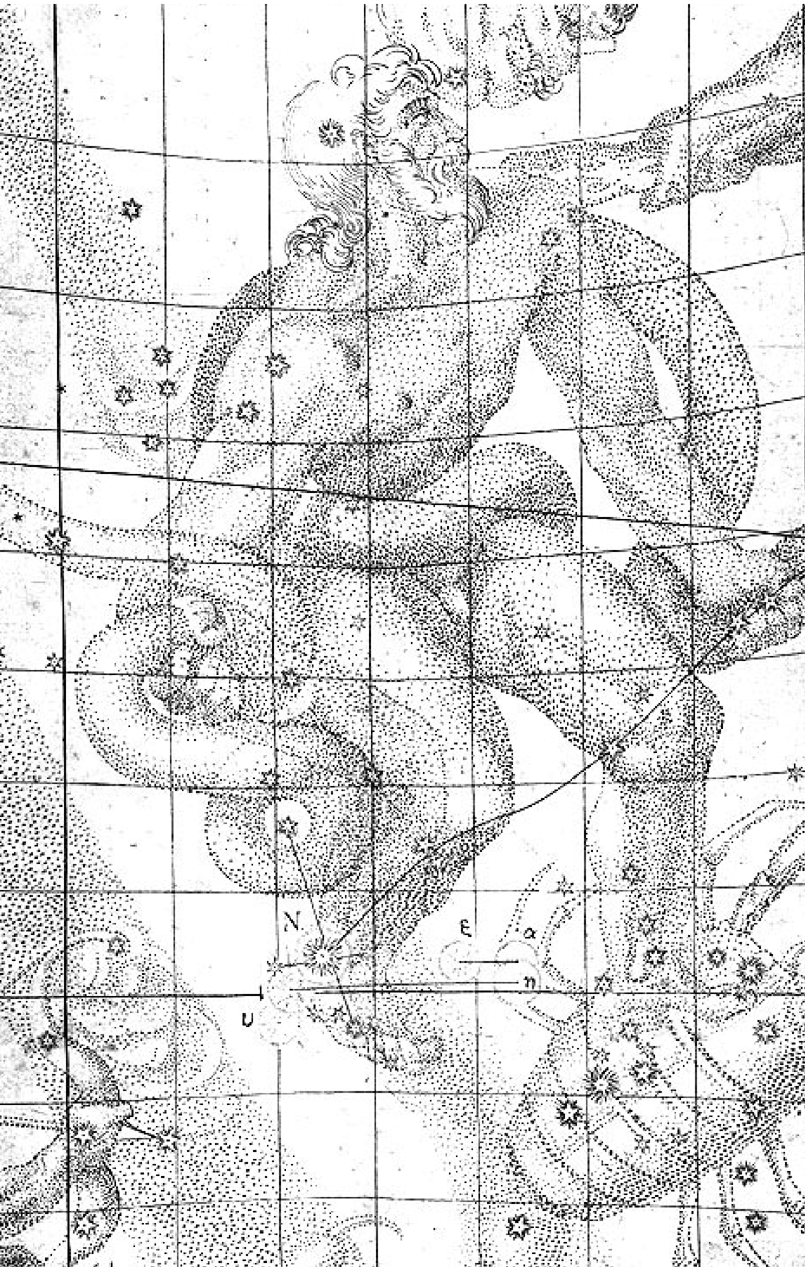
$$\boxed{\phi_{\rm max}/\Phi_{\rm extra} \simeq 0.018}$$

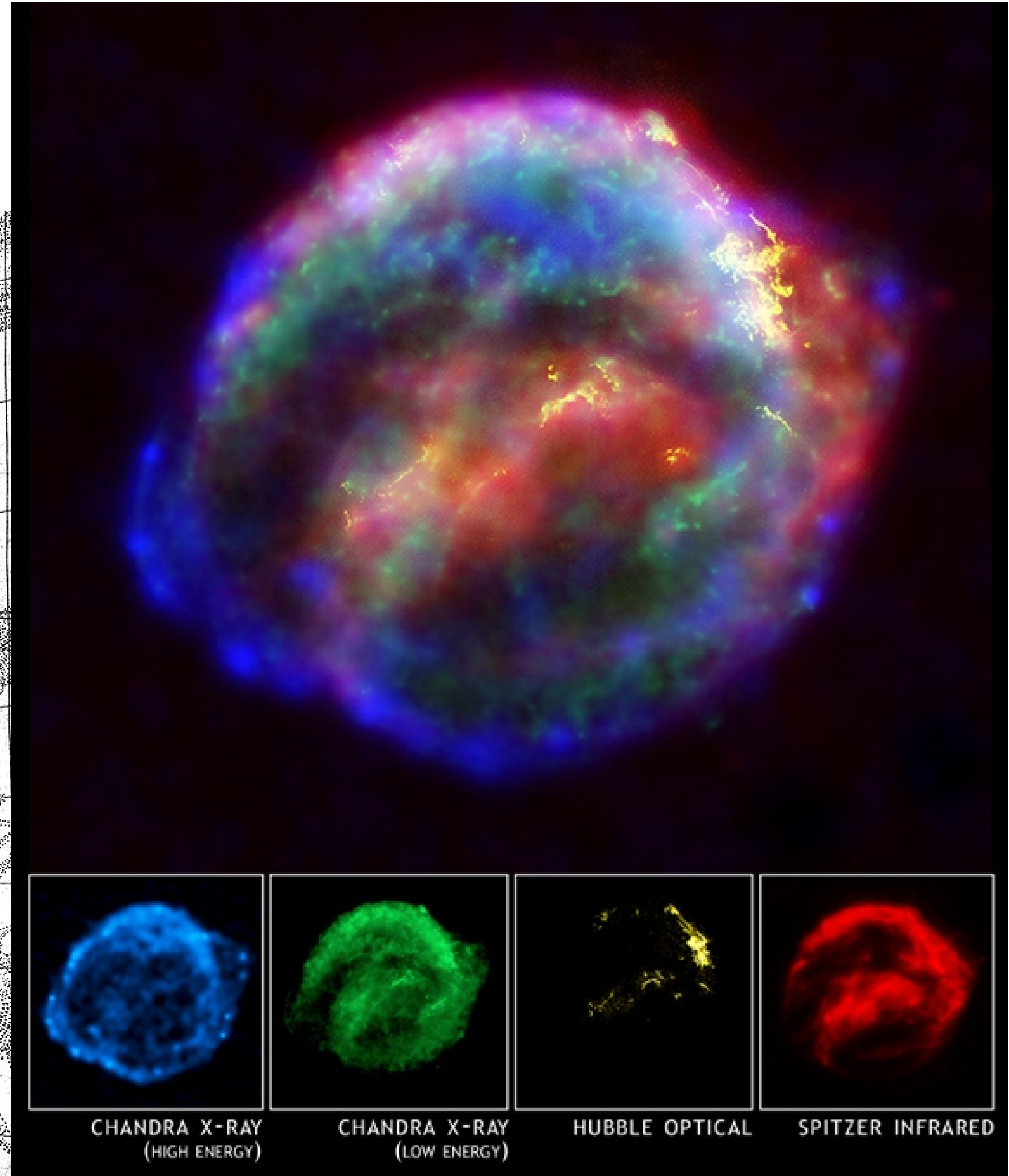


575 (31%)

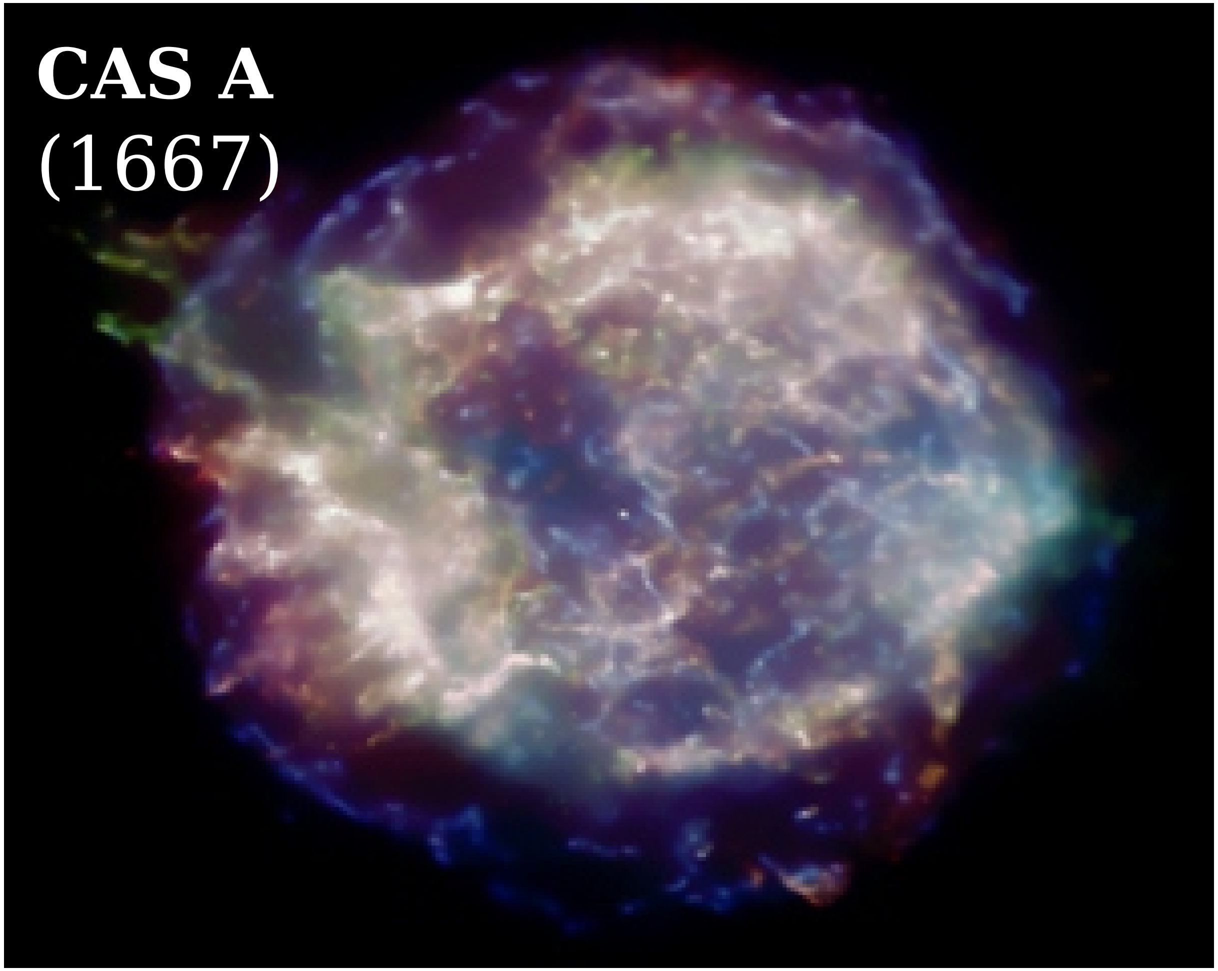
Many unassociated sources...

Johannes Kepler,
De Stella Nova in Pede Serpentarii (1606)





The SuperNova "Paradigm" for CR acceleration



Powering the galactic Cosmic Rays

$$L_{\rm cr}(\text{Milky Way}) \simeq \frac{\rho_{\rm cr}\, V_{\rm conf}}{T_{\rm conf}}$$

$$\simeq 2 \times 10^{41} \left(\frac{\rm erg}{\rm s}\right)$$

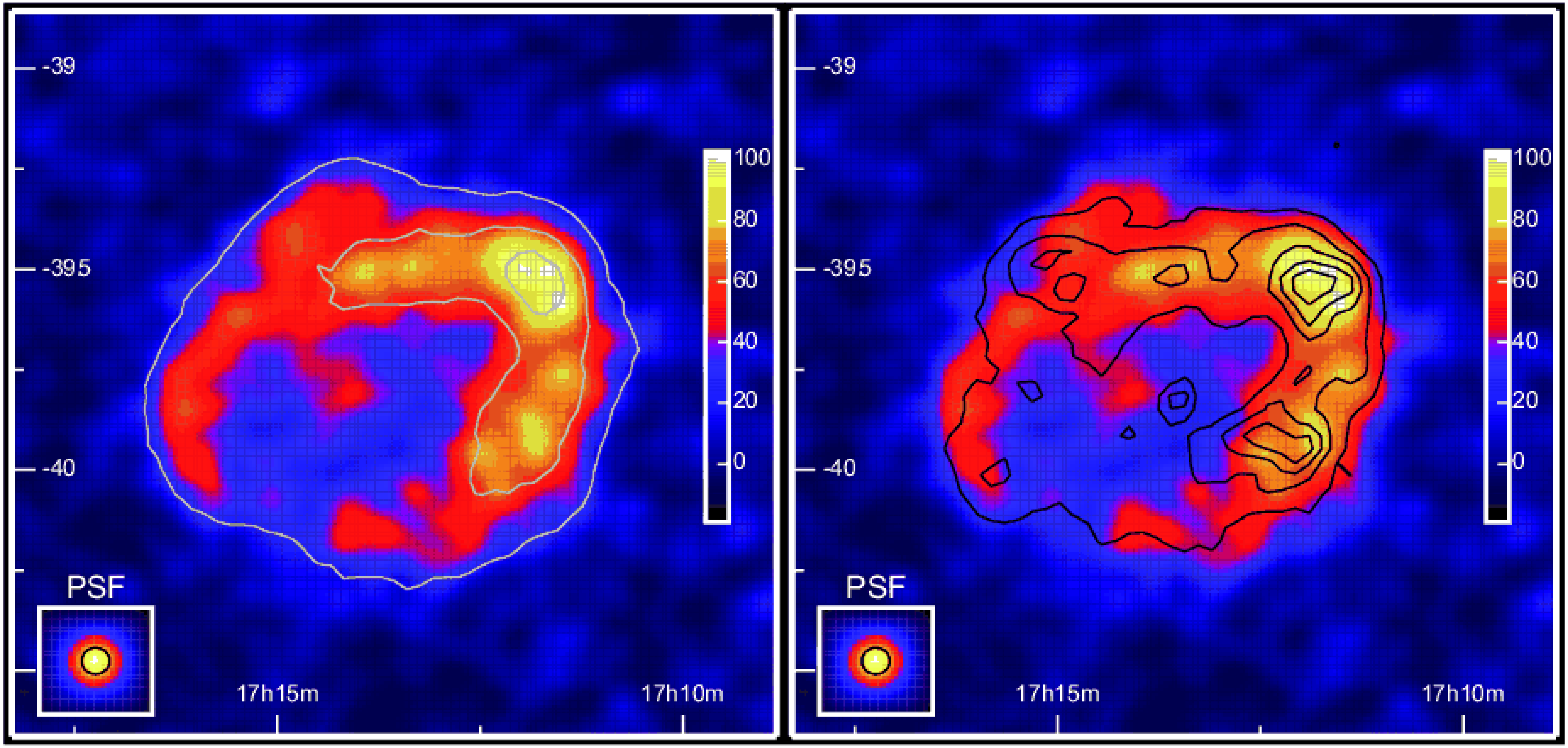
$$\simeq 5 \times 10^{7}\, L_{\odot}$$

- ENERGETICS
- DYNAMICS [Diffusive Shock acceleration]

HESS Telescope

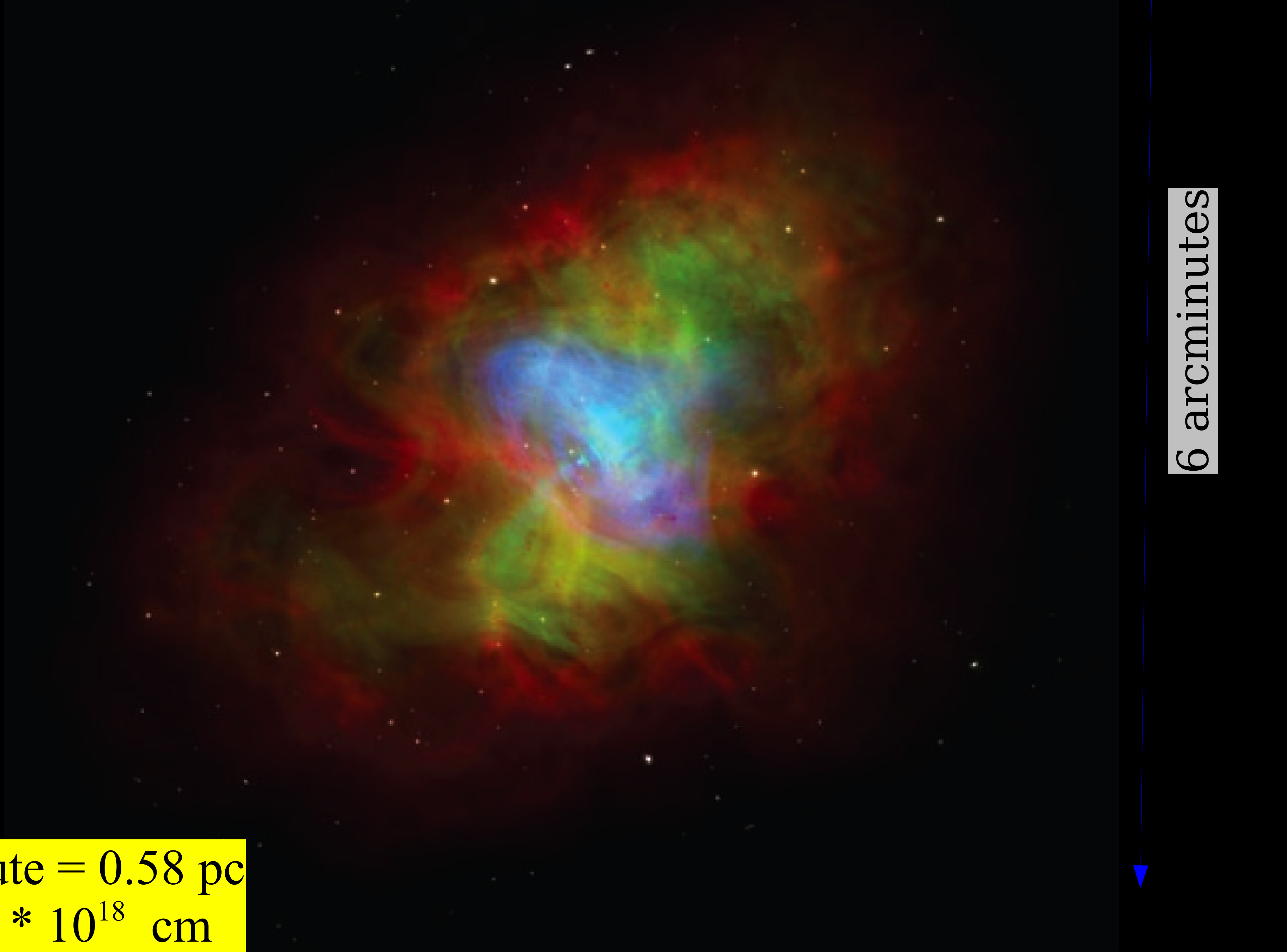
Observations with TeV photons

SuperNova RX J1713.7-3946



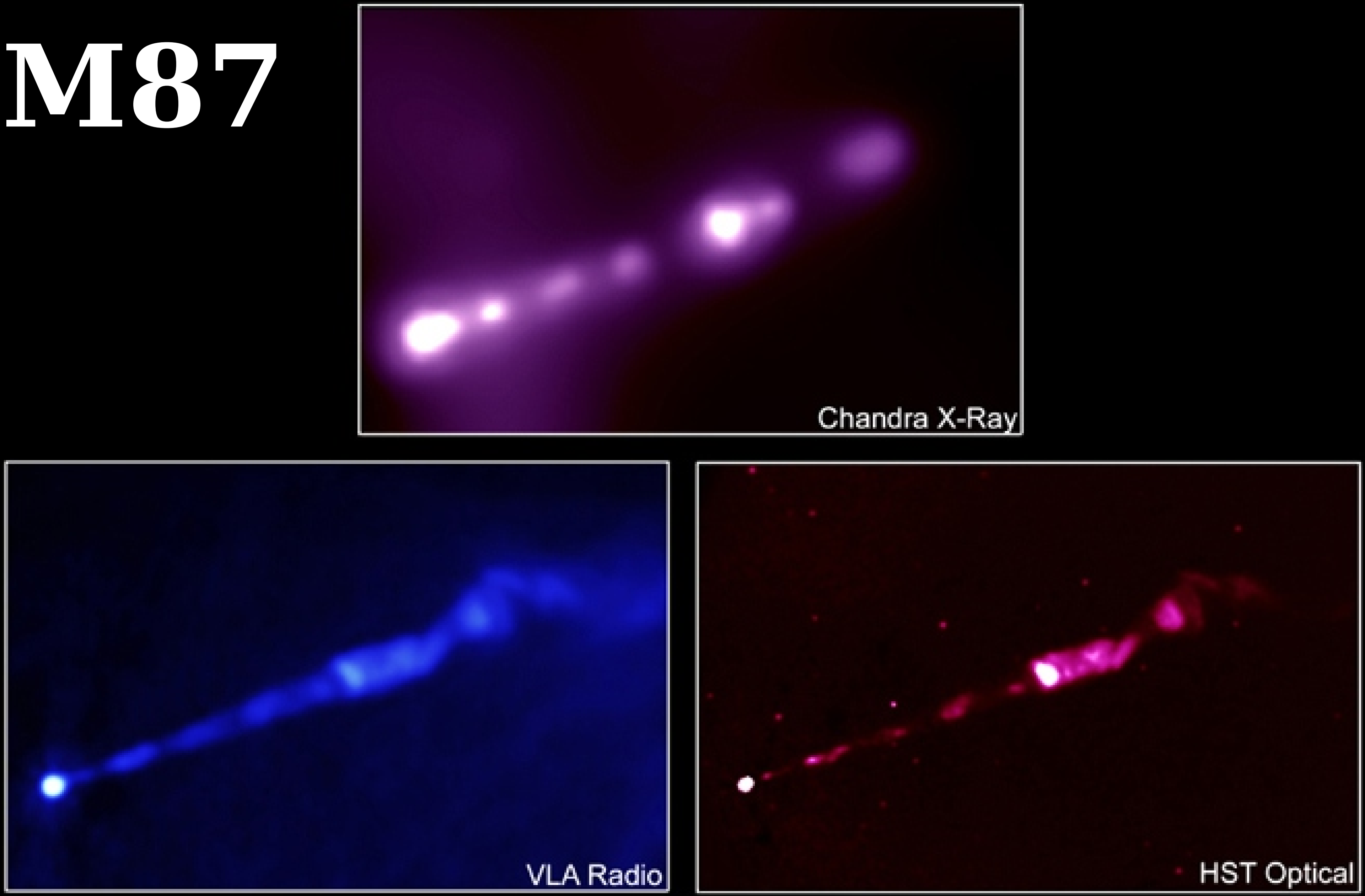
Comparison with ROSAT observation

The CRAB Nebula



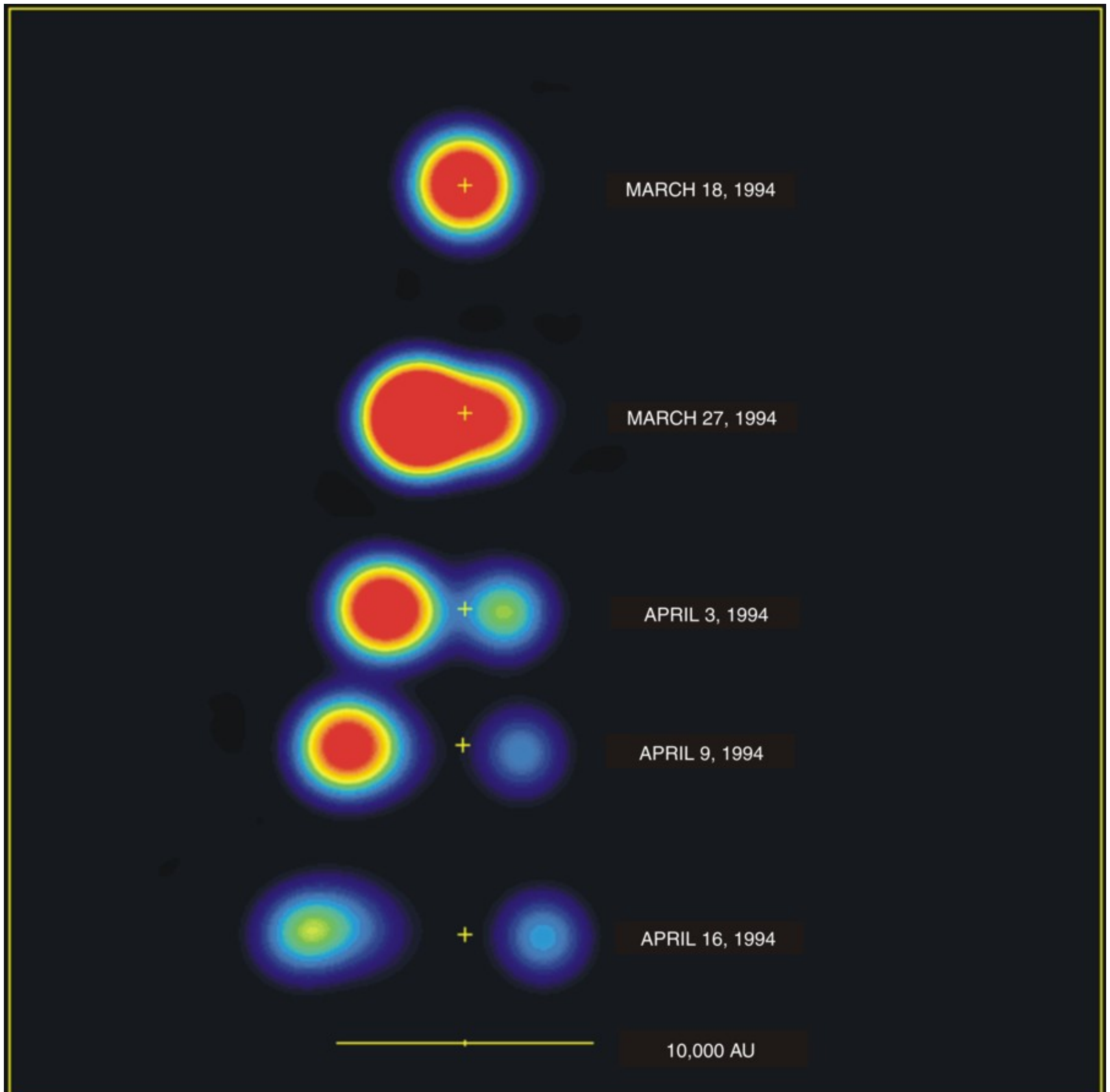
1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

M87



Superluminal Motions in microQuasars
in our Galaxy

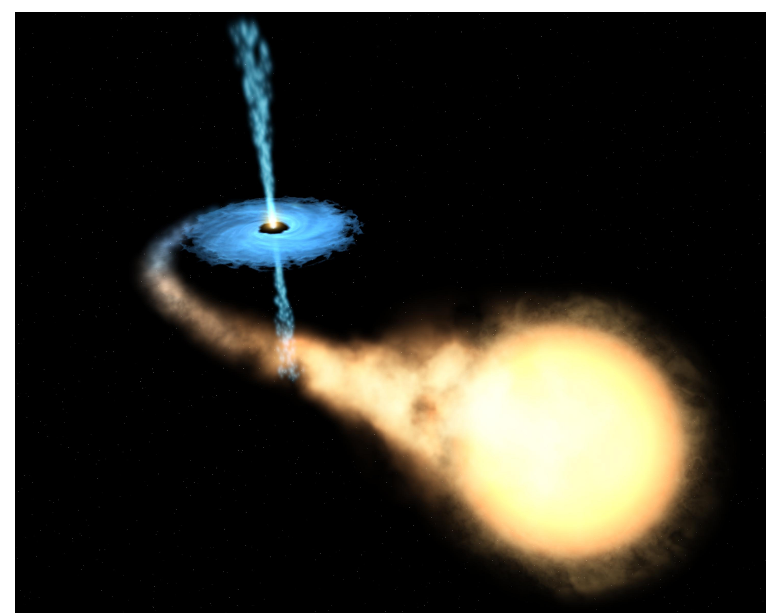
GRS1915+105



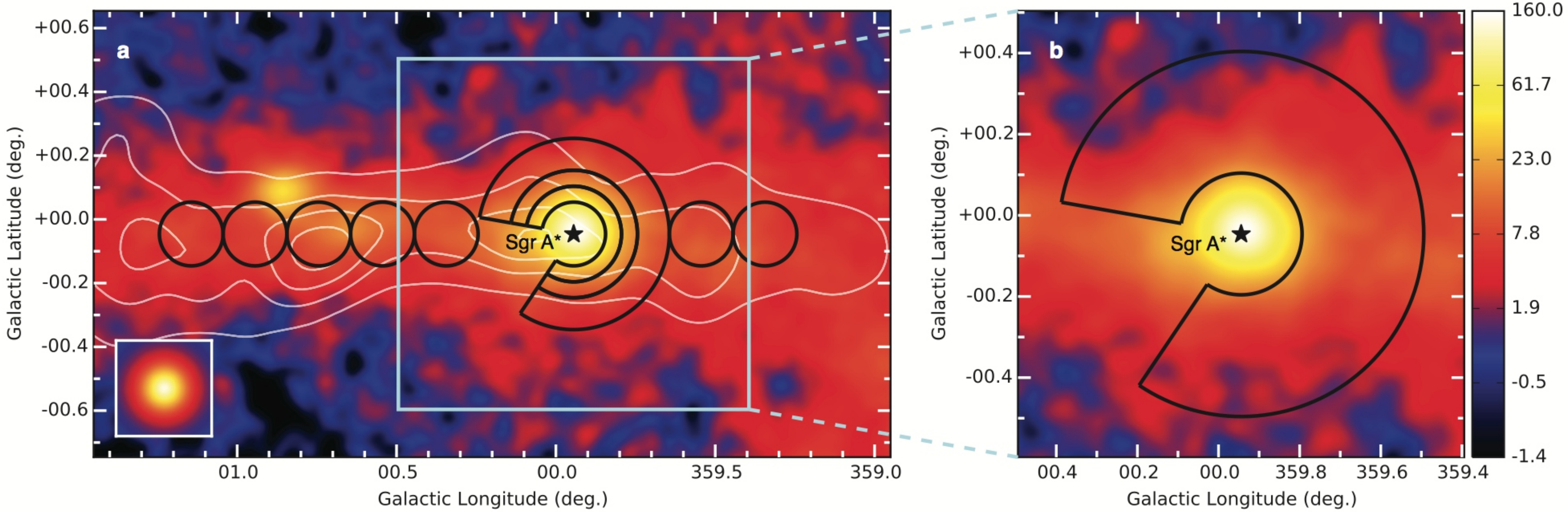
Observations in radio

$$\lambda = 3.5 \text{ cm}$$

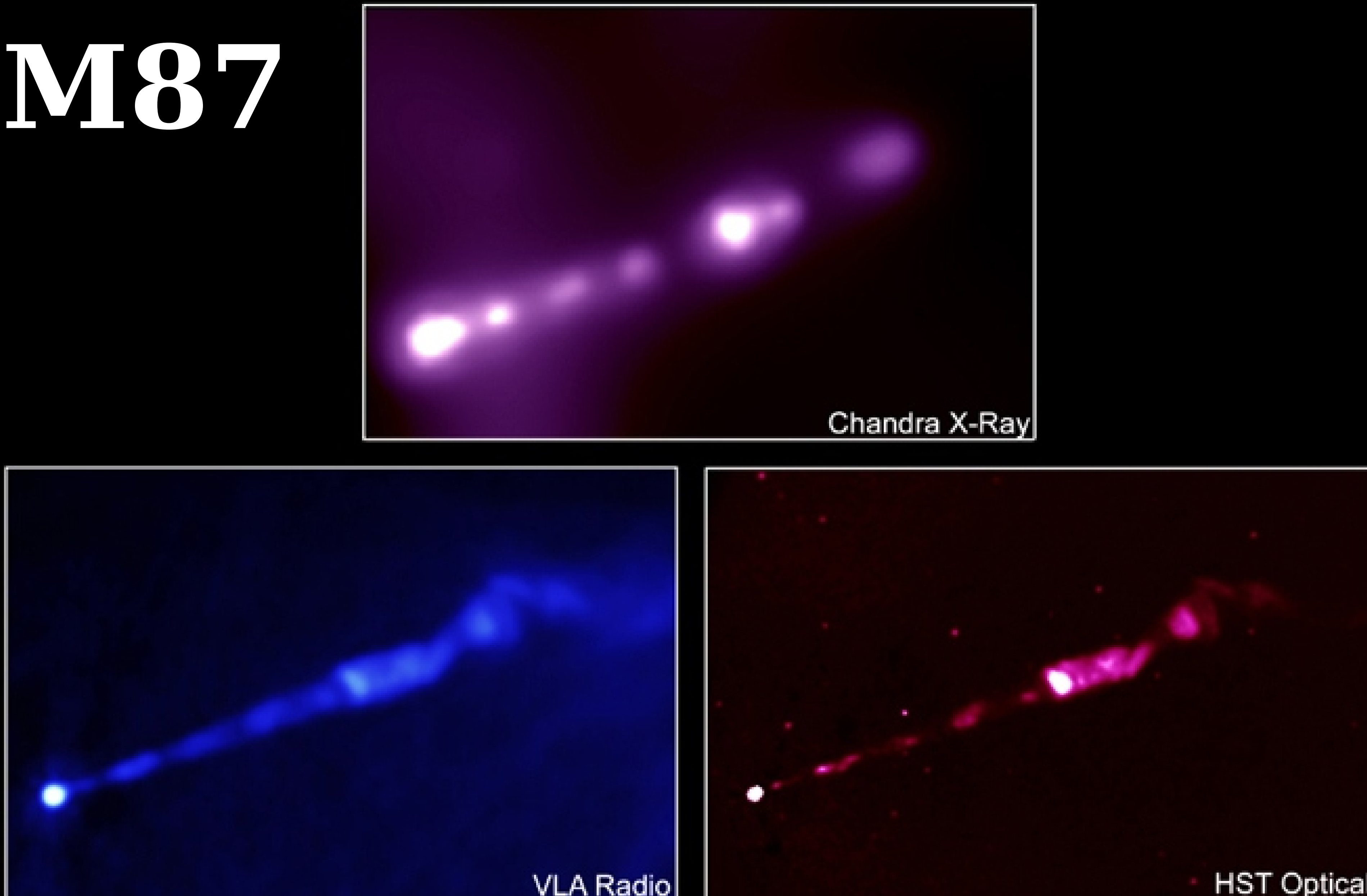
"Two pairs of bright
radio condensations"



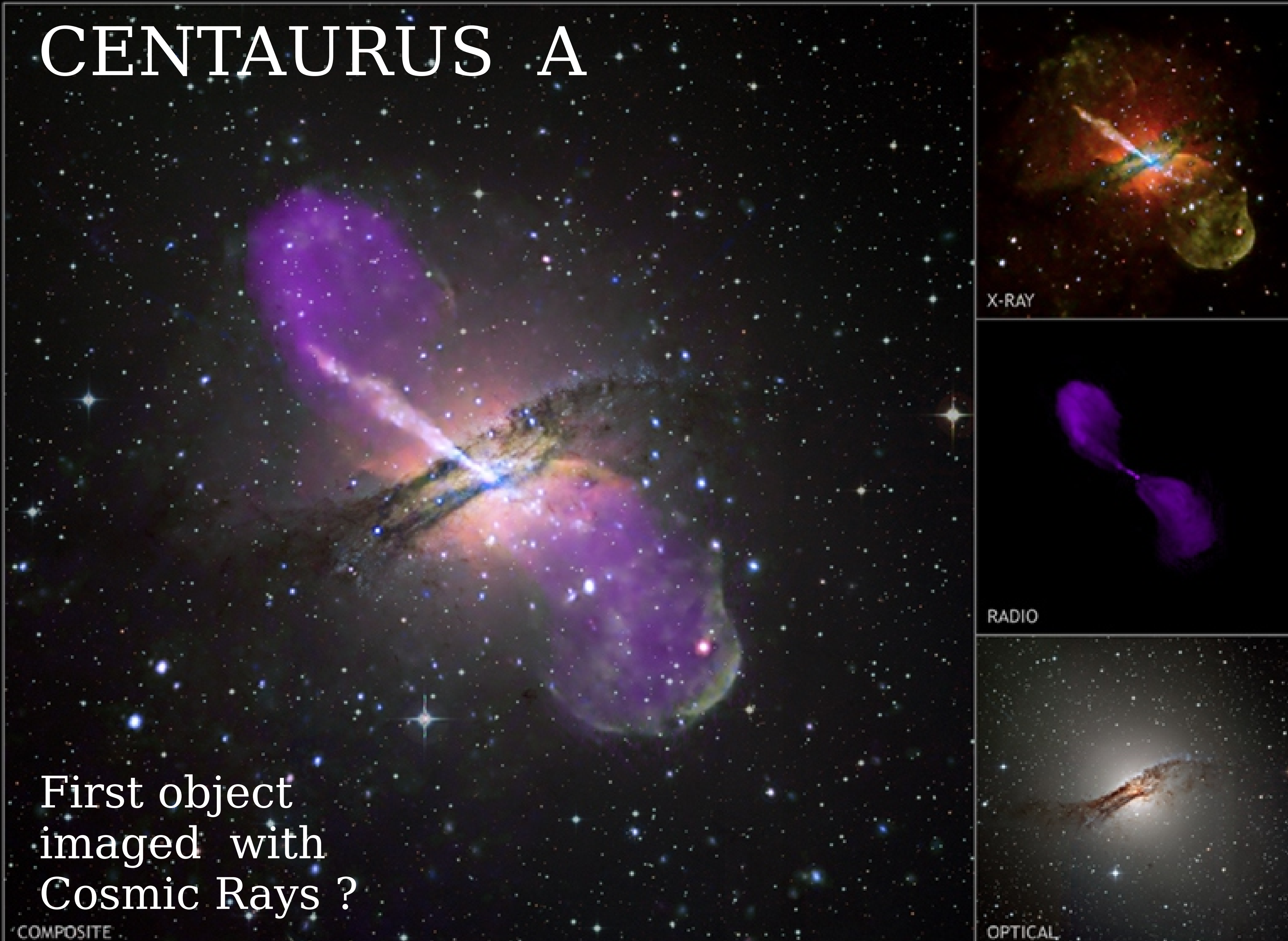
The Galactic Center



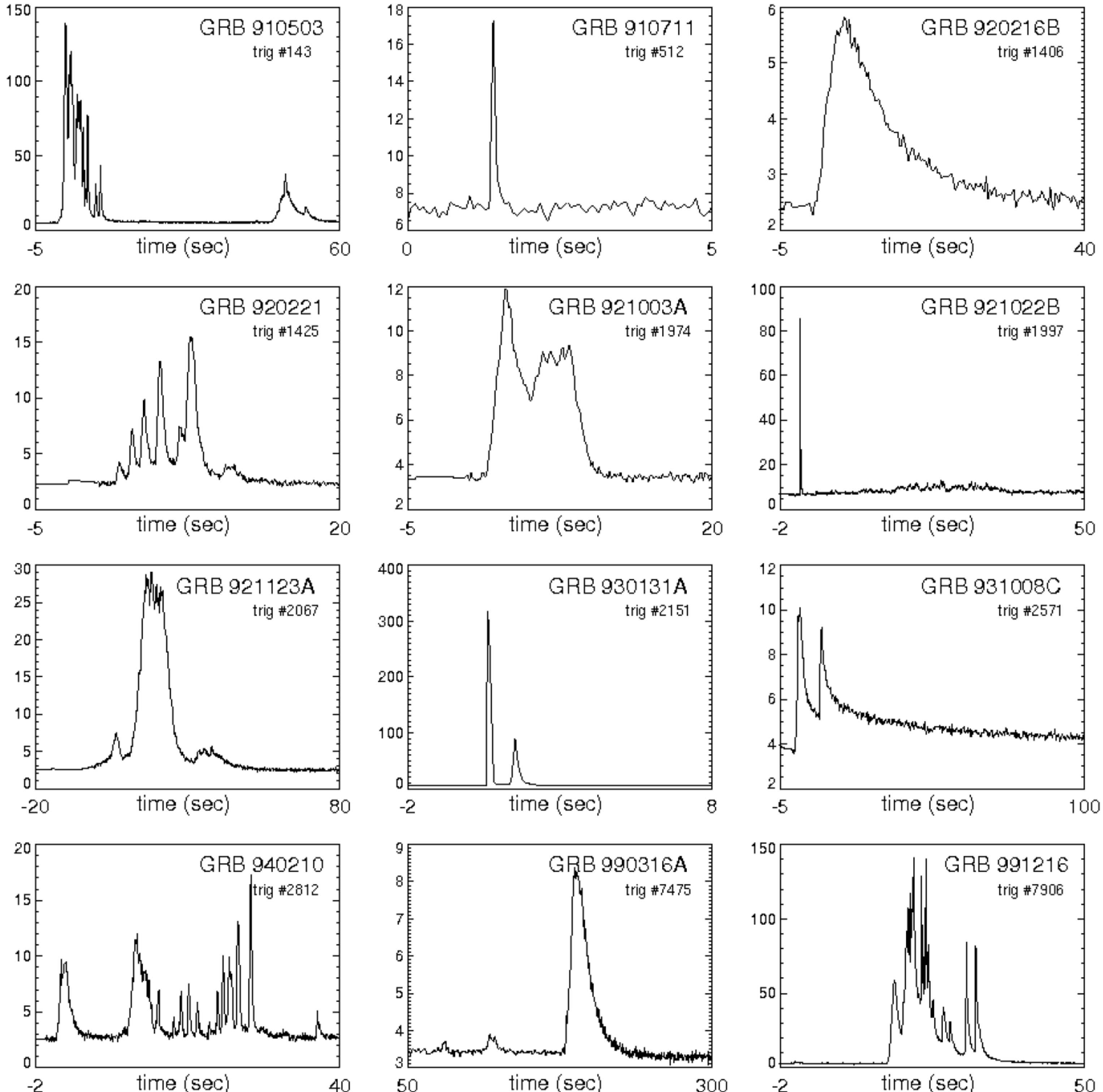
M87

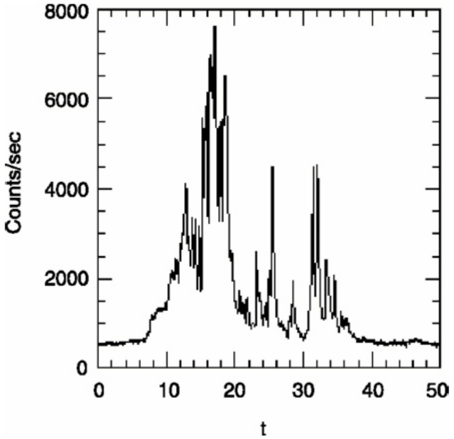


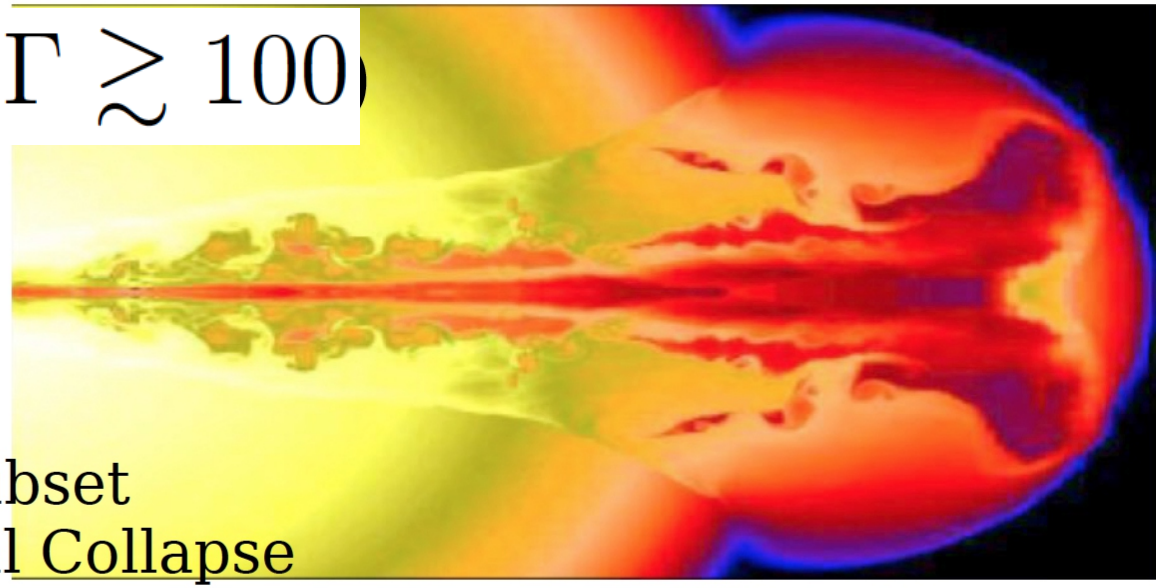
CENTAURUS A



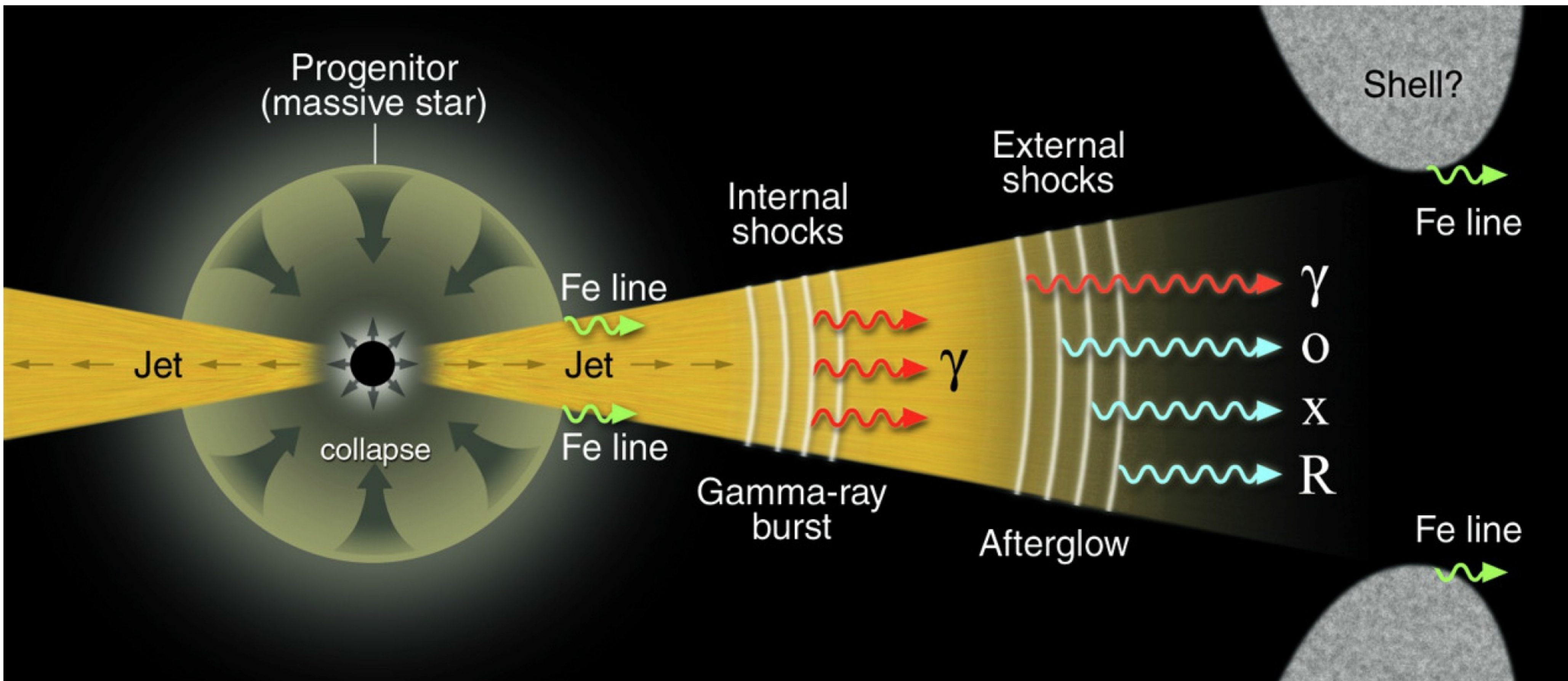
First object imaged with Cosmic Rays ?


GRB 910503
trig #143
GRB 910711
trig #512
GRB 920216B
trig #1406
GRB 920221
trig #1425
GRB 921003A
trig #1974
GRB 921022B
trig #1997
GRB 921123A
trig #2067
GRB 930131A
trig #2151
GRB 931008C
trig #2571
GRB 940210
trig #2812
GRB 990316A
trig #7475
GRB 991216
trig #7906
time (sec)





GRB : associated with a subset
of SN Stellar Gravitational Collapse



6. Astrophysical Neutrinos

- Extragalactic neutrinos
- Diffuse Galactic Neutrinos
- Neutrino Point Sources

GALACTIC

EXTRAGALACTIC

Cosmic Rays

Extragalactic Sources

Source of ultra-relativistic particles

(photons or neutrinos) at redshift z

$$q(E) = \frac{d\dot{N}_{\nu,\gamma}(E)}{dE}$$

Number of particles emitted (isotropically)
per unit time and unit energy

Luminosity
of the source:

$$L = \int dE \; E \; q(E)$$

Flux from a source at redshift z :

$$\phi(E) = q[E(1+z)]\,\frac{1}{4\pi\, r^2(z)}\,\left(\frac{dt_{\rm emission}}{dt_{\rm obs}}\right)\,\left(\frac{dE_{\rm emission}}{dE_{\rm obs}}\right)$$

$$\boxed{\phi(E) = \frac{q[E(1+z)]}{4\pi\, r^2(z)}}$$

$$r(z) = \frac{c}{H_0}\int_0^z \frac{dz}{\sqrt{1+\Omega_{\rm r}\,(1+z)^4 + \Omega_{\rm m}\,(1+z)^3 + \Omega_\Lambda}}$$

Flux observed at the Earth from this source:

$$\phi(E,\ z) = \frac{1}{4\pi\, r^2(z)}\ q[E(1+z)]$$

"comoving distance" of the source r(z)

"energy redshift"

The redshift defines the time when a particle was produced

For linear propagation of a massless particle this also determines the space coordinate

Flux observed at the Earth from this source:

$$\phi(E,\ z) = \frac{1}{4\pi\, r^2(z)}\ q[E(1+z)]$$

"comoving distance" of the source r(z)

"energy redshift"

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$= \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{1 + \Omega_\mathrm{r}\,(1+z')^4 + \Omega_\mathrm{m}\,(1+z')^3 + \Omega_\Lambda}}$$

Bolometric energy flux from a source at redshift z

$$\phi(E) = \frac{q[E(1+z)]}{4\pi\, r^2(z)}$$

$$\mathcal{F} = \int_0^\infty dE\ E\ \phi(E)$$

$$= \frac{1}{4\,\pi\, r^2(z)} \int dE\ E\ q[E(1+z)]$$

$$= \frac{1}{4\,\pi\, r^2(z)}\ \frac{1}{(1+z)^2} \int_0^\infty dE'\ E'\ q(E')$$

$$= \frac{L}{4\,\pi\, r^2(z)\,(1+z)^2}$$

$$\mathcal{F} = \frac{L}{4\,\pi\, d_L^2(z)}$$

$$d_L(z) = r(z)\,(1+z)$$

Flux from the sum of all extragalactic sources

$$\langle q(E,z) \rangle$$

Average emission
per unit time,
unit volume,
unit of energy
[at time t (or redshift z)]

All identical sources:

$$\langle q(E,z) \rangle = n_{\rm sources}(z)\; q_s(E)$$

The generalization for multiple types of sources
is straightforward (summing over all “classes”
or types of sources)_

$$\phi_{\mathrm{extra}}(E) = \frac{1}{4\pi} \int_0^\infty dz \, \frac{dV}{dz} \, \frac{\langle q[E(1+z)] \rangle}{4\pi \, r^2(z)}$$

$$\frac{dV}{dz} = 4\pi \, r^2(z) \, \frac{dr}{dz}$$

$$\frac{dr}{dz} = \frac{1}{h(z)}$$

$$h(z) = \sqrt{1 + \Omega_{\mathrm{r}} \, (1+z)^4 + \Omega_{\mathrm{m}} \, (1+z)^3 + \Omega_\Lambda}$$

$$\boxed{\phi_{\mathrm{extra}}(E) = \frac{1}{4\,\pi} \, \frac{c}{H_0} \int_0^\infty \frac{dz}{h(z)} \, \langle q[E(1+z)] \rangle}$$

Total sum of extragalactic sources:

$$\phi_{\rm extra}(E) = \frac{1}{4\,\pi}\;\frac{c}{H_0}\;\int_0^\infty \frac{dz}{h(z)}\,\langle q[E(1+z)]\rangle$$

Derivation assuming *linear propagation*
of the particles [and no absorption or energy losses
(except for the universal redshift effects)]

Alternative (and simpler) derivation that is also valid
For non linear propagation (Cosmic Rays)

Relation between an isotropic flux
and the (ultra-relativistic) particle density

$$\phi(E) = \frac{c}{4\pi}\, n(E)$$

Compute the density (now) of particles
need to integrate over the history of the injection

$$n(E) = \int dt \int dE_0 \, \langle q(E_0, t)\rangle \, \delta\left[E - \frac{E_0}{(1+z)}\right]$$

$$n(E) = \int_0^\infty dz \, \left|\frac{dt}{dz}\right| \, (1+z) \, \langle q[E(1+z), z]\rangle$$

$$n(E) = \int_0^\infty dz \; \left| \frac{dt}{dz} \right| \; (1+z) \; \langle q[E(1+z), z] \rangle$$

$$n(E) = \frac{1}{H_0} \int_0^\infty \frac{dz}{h(z)} \; q[E(1+z), z]$$

$$\phi_{\mathrm{extra}}(E) = \frac{c}{4\,\pi} \, \frac{1}{H_0} \int_0^\infty \frac{dz}{h(z)} \, \langle q[E(1+z)] \rangle$$

The “Olbers (Kepler) Paradox”

Static, Homogeneous, Euclidean space
Filled with identical sources of Luminosity L

$$\ell = \frac{L}{4\,\pi\,R^2}$$

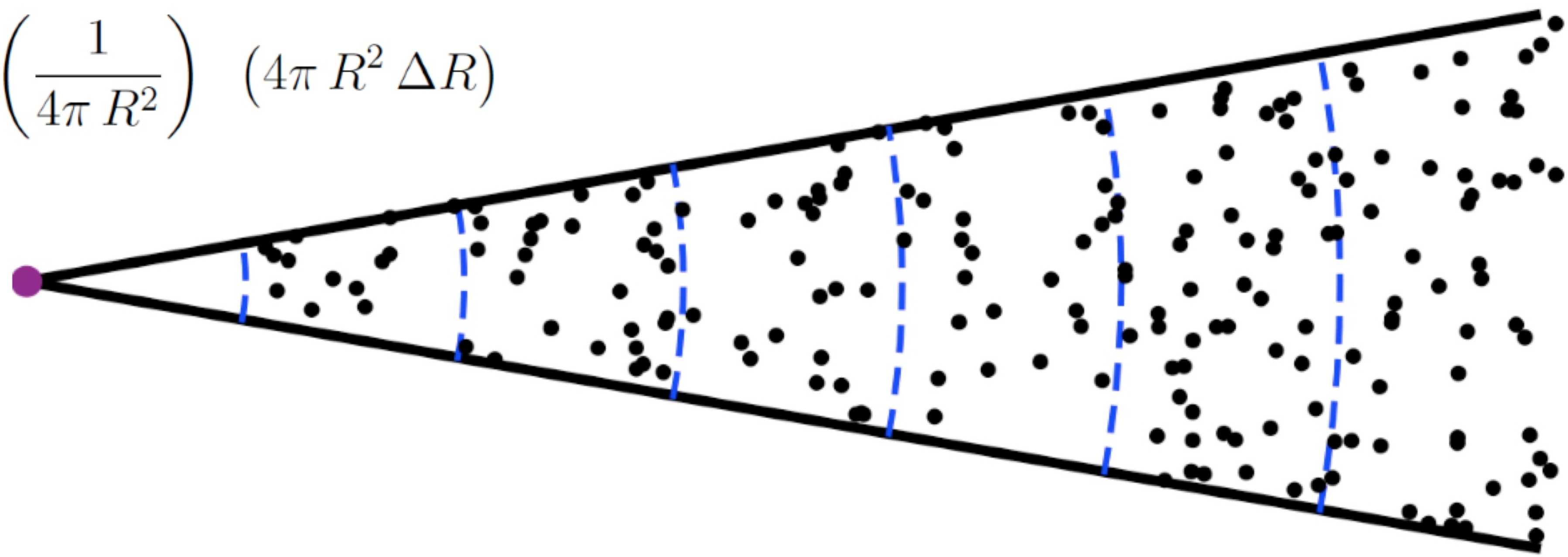
Apparent luminosity
of a source ad distance R

$$\left.\frac{dF}{d\Omega}\right|_{\text{inclusive}} = \frac{1}{4\pi} \int_0^\infty dR\,(4\,\pi\,n_s\,R^2)\,\frac{L}{4\,\pi\,R^2}$$

$$= \frac{n_s\,L}{4\,\pi} \int_0^\infty dR\,1 \longrightarrow \infty$$

Isotropic flux generated by the ensemble of all (extragalactic) sources in the universe.

$$\left(\frac{1}{4\pi\, R^2}\right) \quad (4\pi\, R^2\, \Delta R)$$

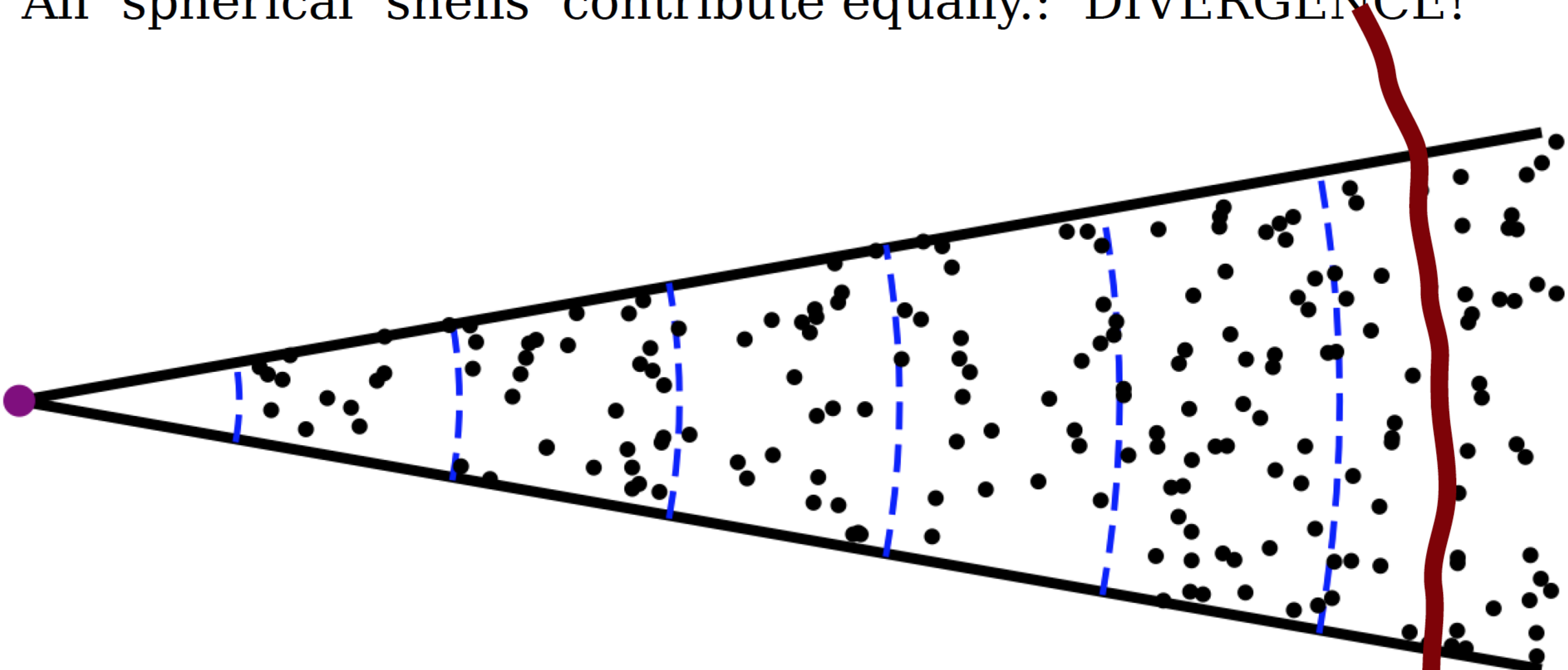


Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!

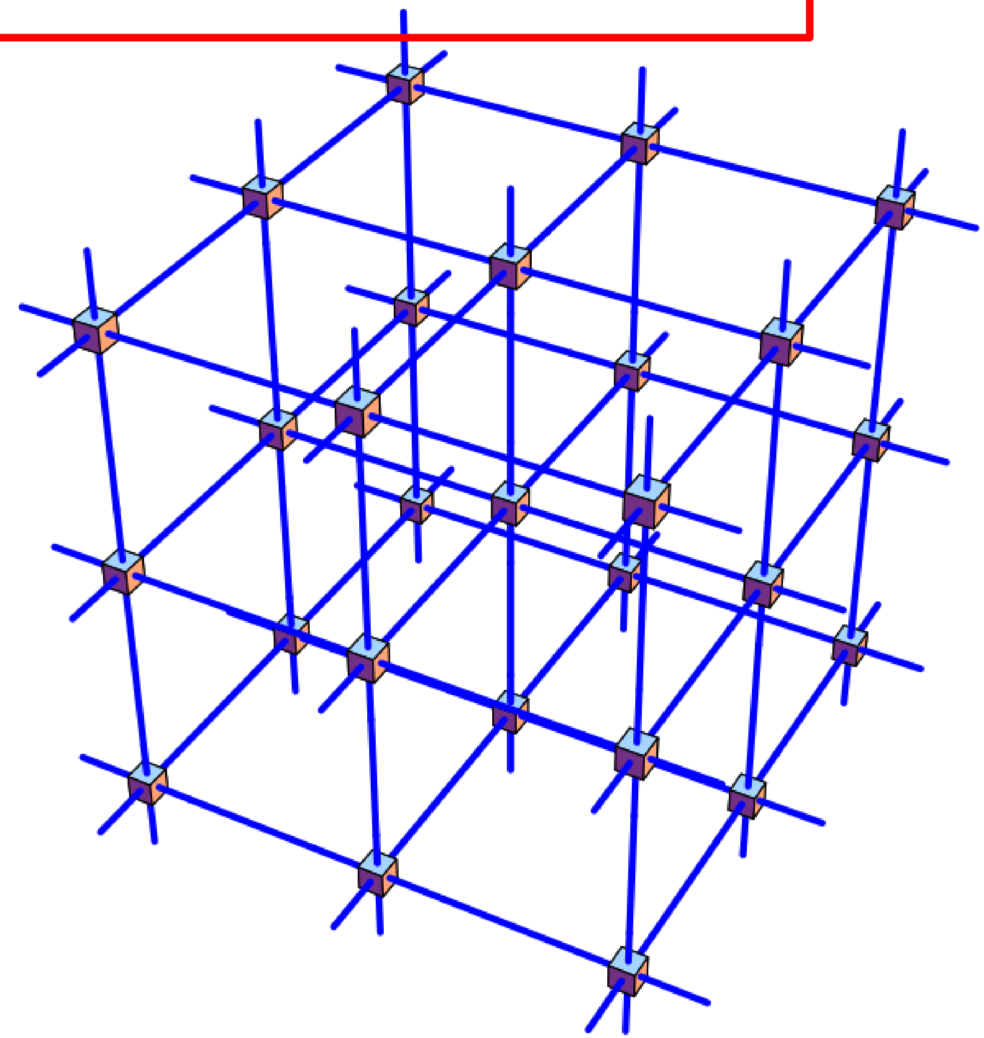


Divergence cured
By cosmological effects

$$\left(\frac{1}{4\pi R^2}\right) \quad (4\pi R^2 \Delta R)$$

$$\boxed{R_{\text{Hubble}} = \frac{c}{H_0} \simeq 3 \text{ Gpc}}$$

The 3-dimensional lampposts ensemble "paradox" [Kepler – Olbers paradox].

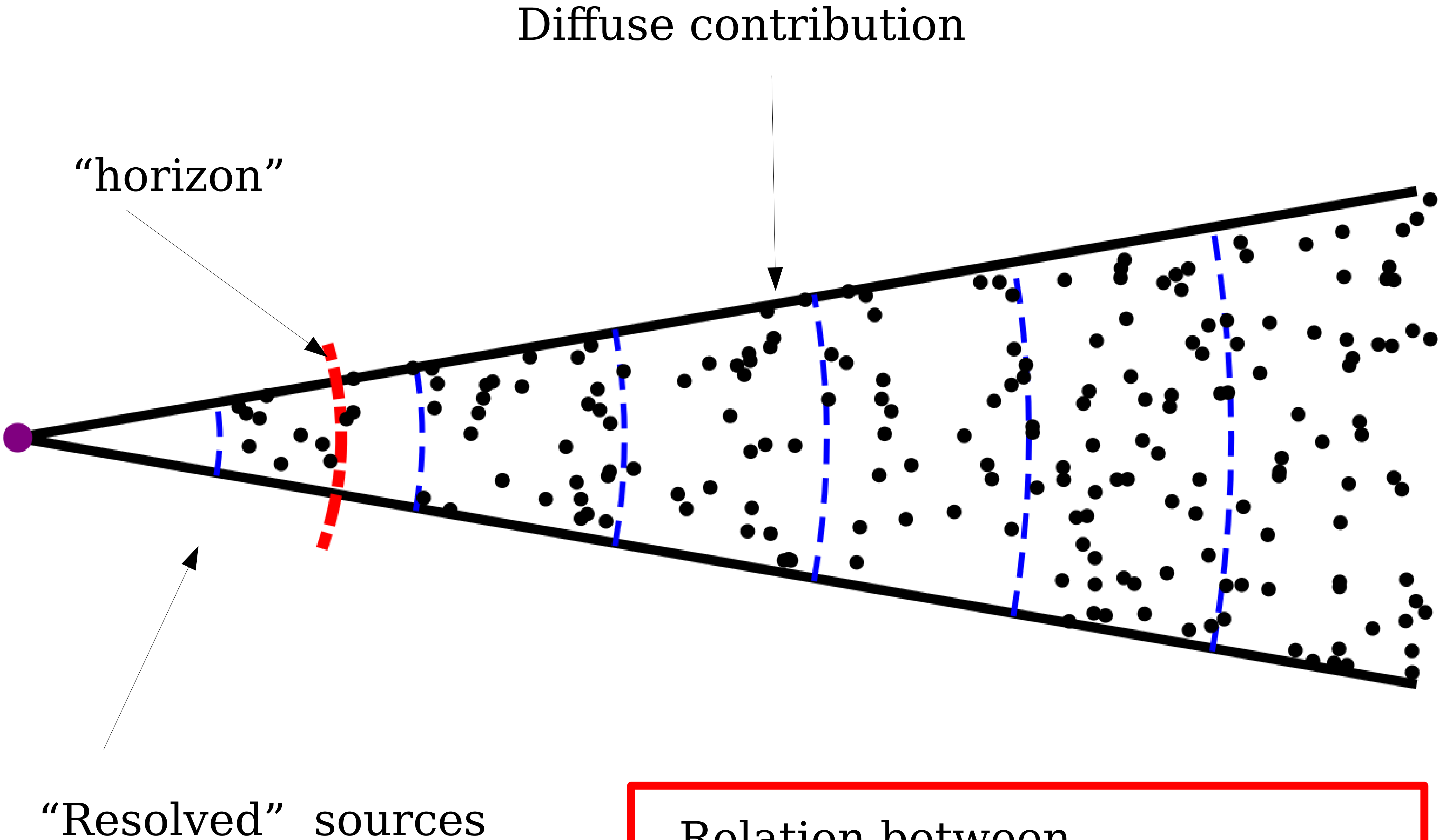


Linear sequence of lamp-posts:

Most of the light you receive from the nearest lamppost

3D ensemble of lampposts: [Euclidean static space]

Light diverges !



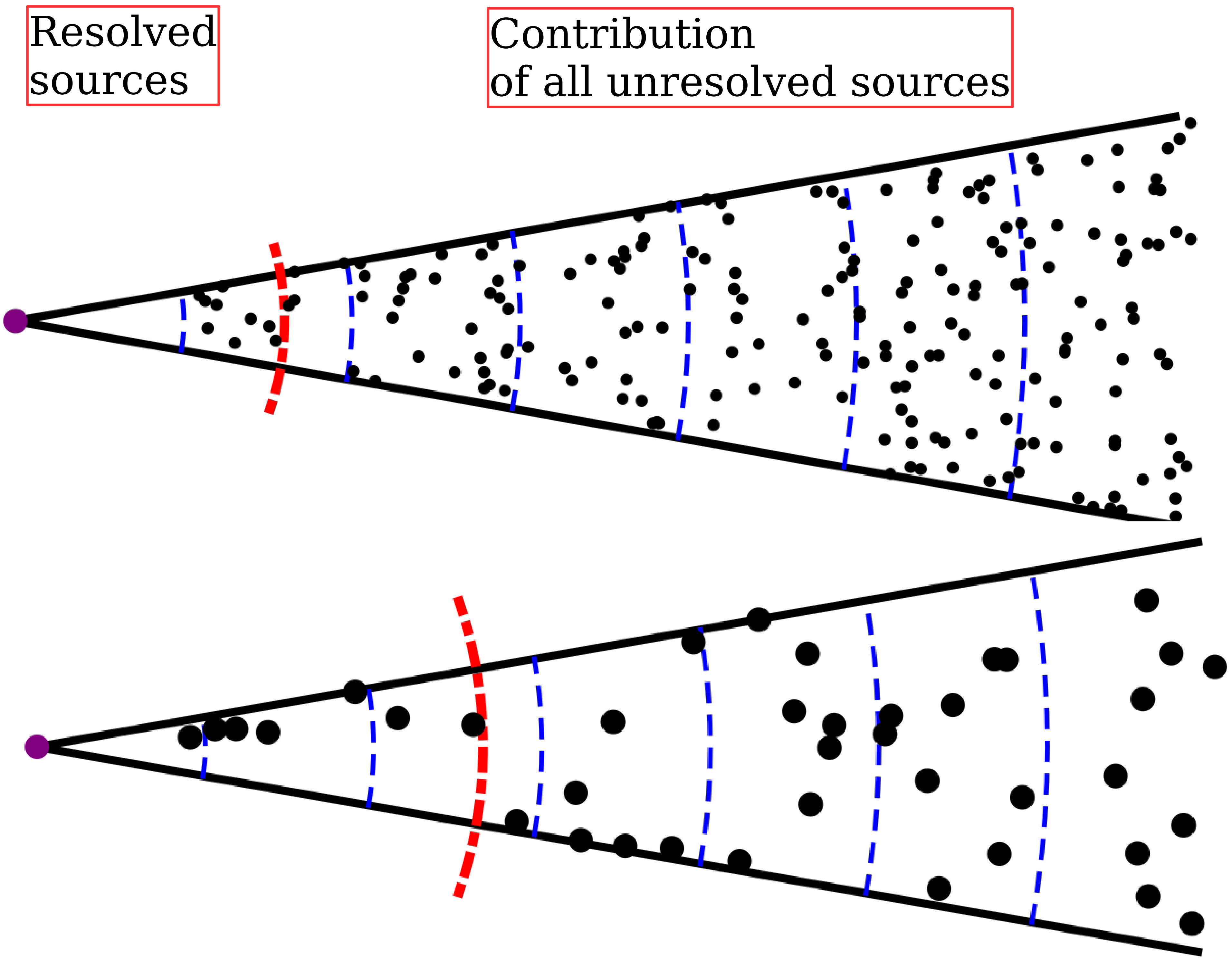
Relation between
The diffuse flux
And the detected Point Sources

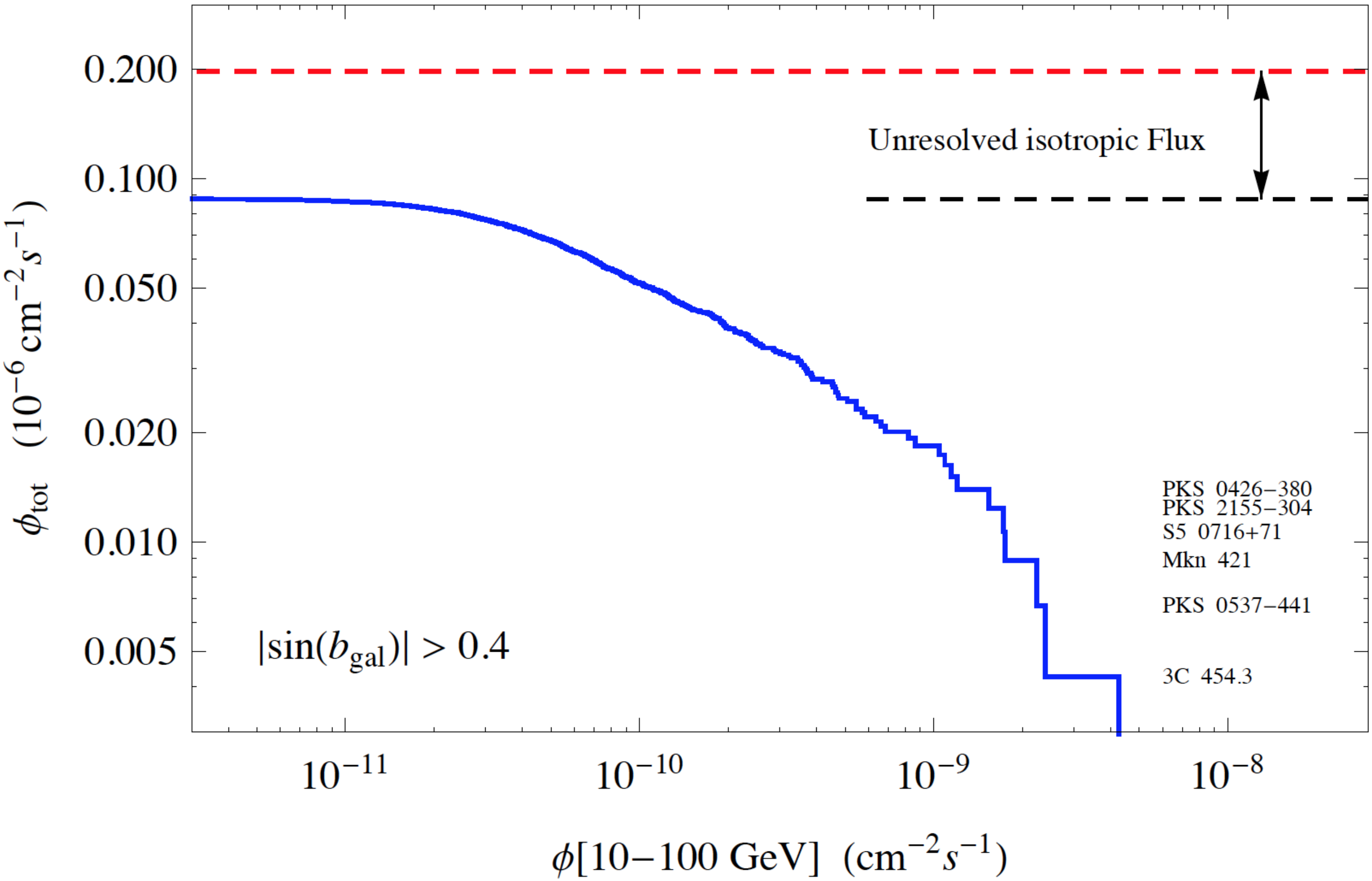
$$\frac{dN_s}{d\ell} = \frac{dN_s}{dR}\,\frac{dR}{d\ell} = 4\,\pi\;n_s\;\left[R^2\;\left|\frac{d\ell}{dR}\right|^{-1}\right]_{R=\sqrt{\frac{L}{4\,\pi}}} = 4\,\pi\;n_s\;\left(\frac{L}{4\,\pi}\right)^{3/2}\;\frac{\ell^{-5/2}}{2}$$

$$N_s(\geq \ell_{\min}) = \int_{\ell_{\min}}^{\infty} d\ell\;\frac{dN_s}{d\ell} = n_s\;\frac{4\pi}{3}\;\left(\frac{L}{4\,\pi\;\ell_{\min}}\right)^{3/2}$$

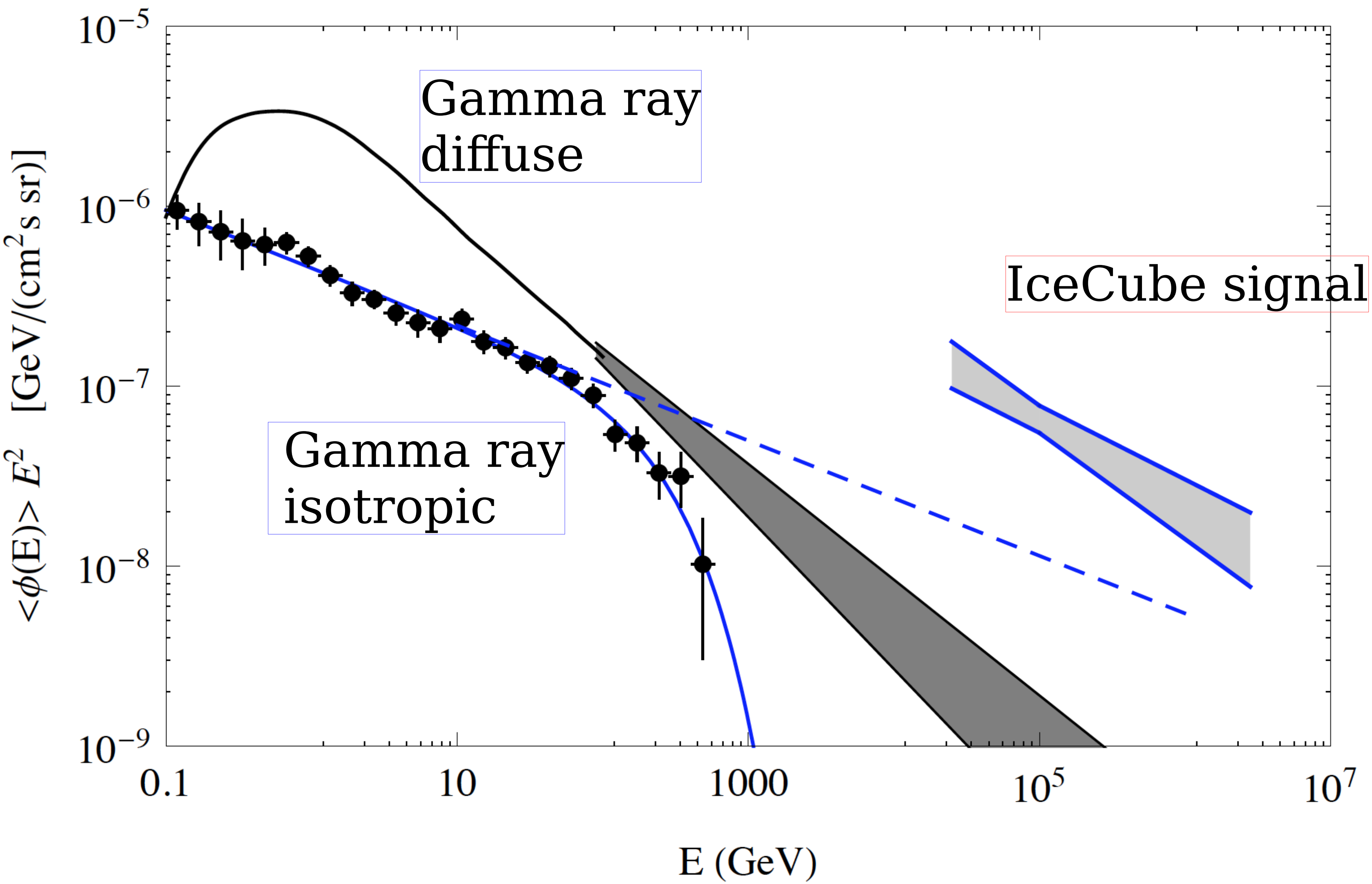
$$R_{\ell_{\min}} = \sqrt{L/(4\pi\ell_{\min})}$$

$$\boxed{\begin{aligned} &N_s(\geq \ell_{\min}) \propto R^3_{\ell_{\min}} \propto \ell_{\min}^{-3/2} \\ &\text{Energy Flux}[\geq \ell_{\min}] \propto \ell_{\min}\;R^3_{\ell_{\min}} \propto \ell_{\min}^{-1/2} \end{aligned}}$$

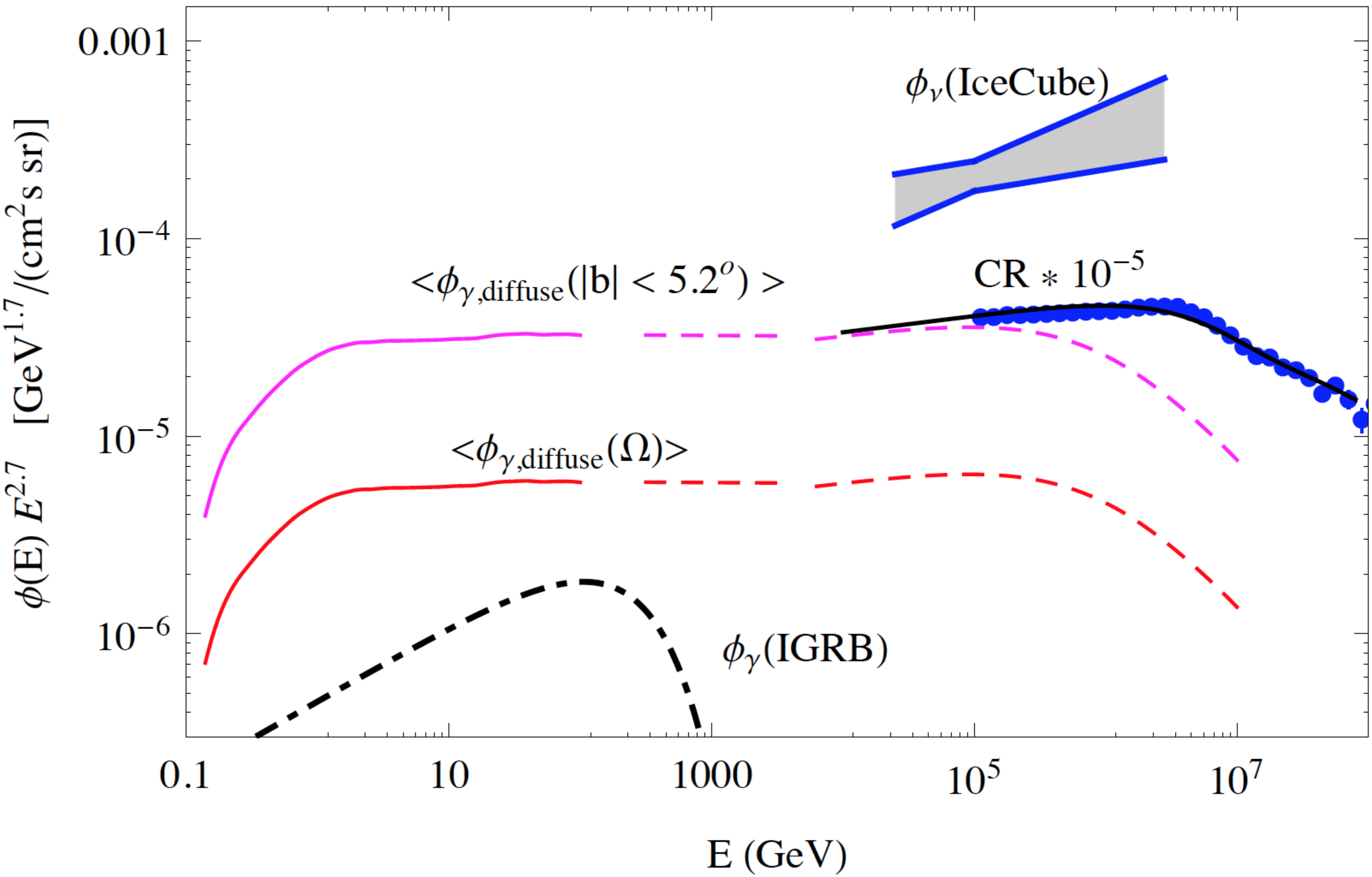

Resolved sources
Contribution of all unresolved sources



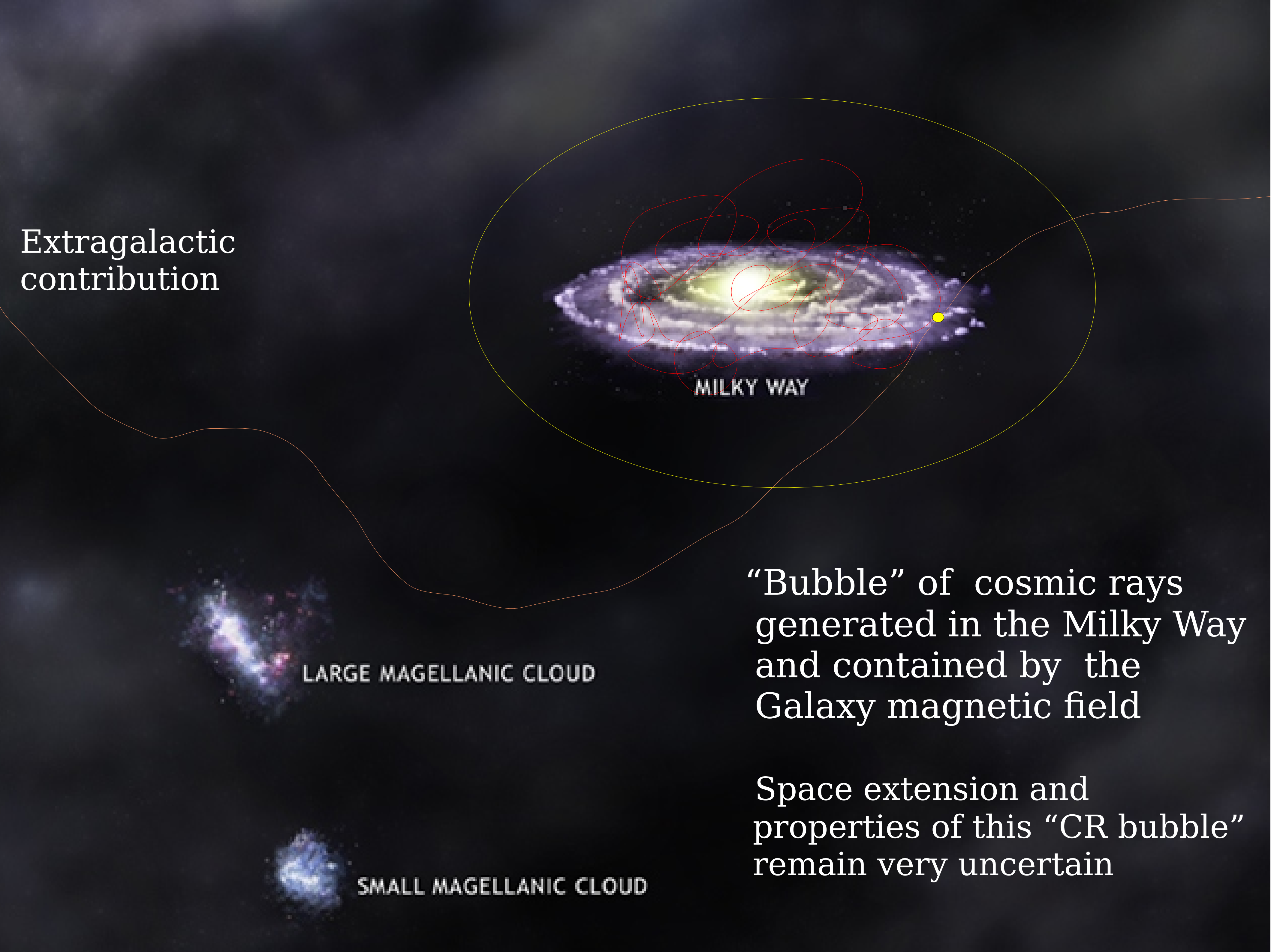
0.200
0.100
0.050
0.020
0.010
0.005
$\phi_{\rm tot}$ $(10^{-6}\,{\rm cm}^{-2}s^{-1})$
10^{-11}
10^{-10}
10^{-9}
10^{-8}
$\phi[10-100\ {\rm GeV}]$ $({\rm cm}^{-2}s^{-1})$
Unresolved isotropic Flux
$|\sin(b_{\rm gal})| > 0.4$
PKS 0426−380
PKS 2155−304
S5 0716+71
Mkn 421
PKS 0537−441
3C 454.3



Gamma ray diffuse
IceCube signal
Gamma ray isotropic
$<\phi(E)> E^2$ [GeV/(cm^{2}s sr)]
E (GeV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.1
10
1000
10^5
10^7



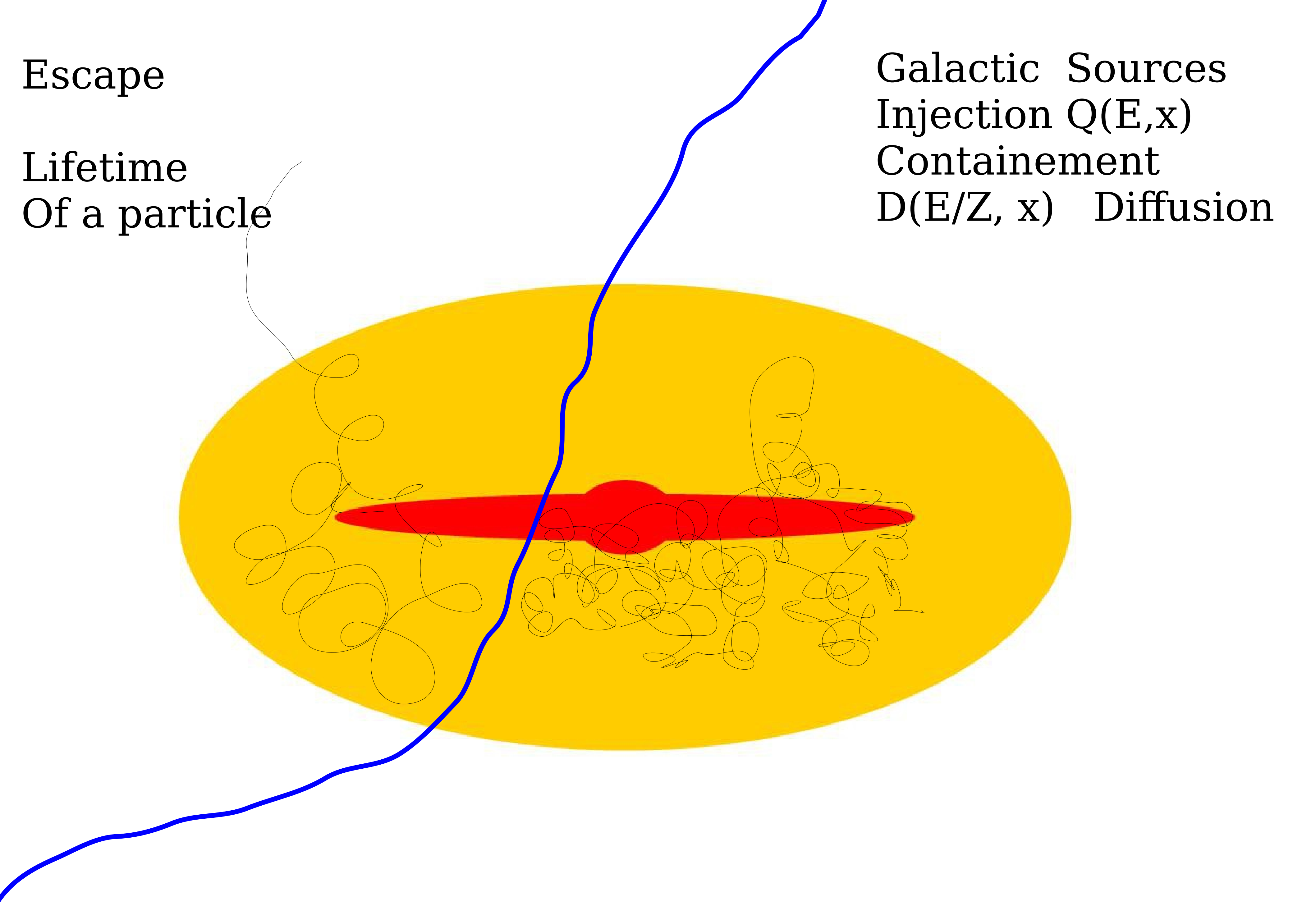
0.001
10^{-4}
10^{-5}
10^{-6}
$\phi(E)\ E^{2.7}$ [GeV$^{1.7}$/(cm^{2}s sr)]
ϕ_ν(IceCube)
CR $*\ 10^{-5}$
$<\phi_{\gamma,\mathrm{diffuse}}(|b| < 5.2^o) >$
$<\phi_{\gamma,\mathrm{diffuse}}(\Omega)>$
ϕ_γ(IGRB)
0.1
10
1000
10^5
10^7
E (GeV)



Extragalactic contribution

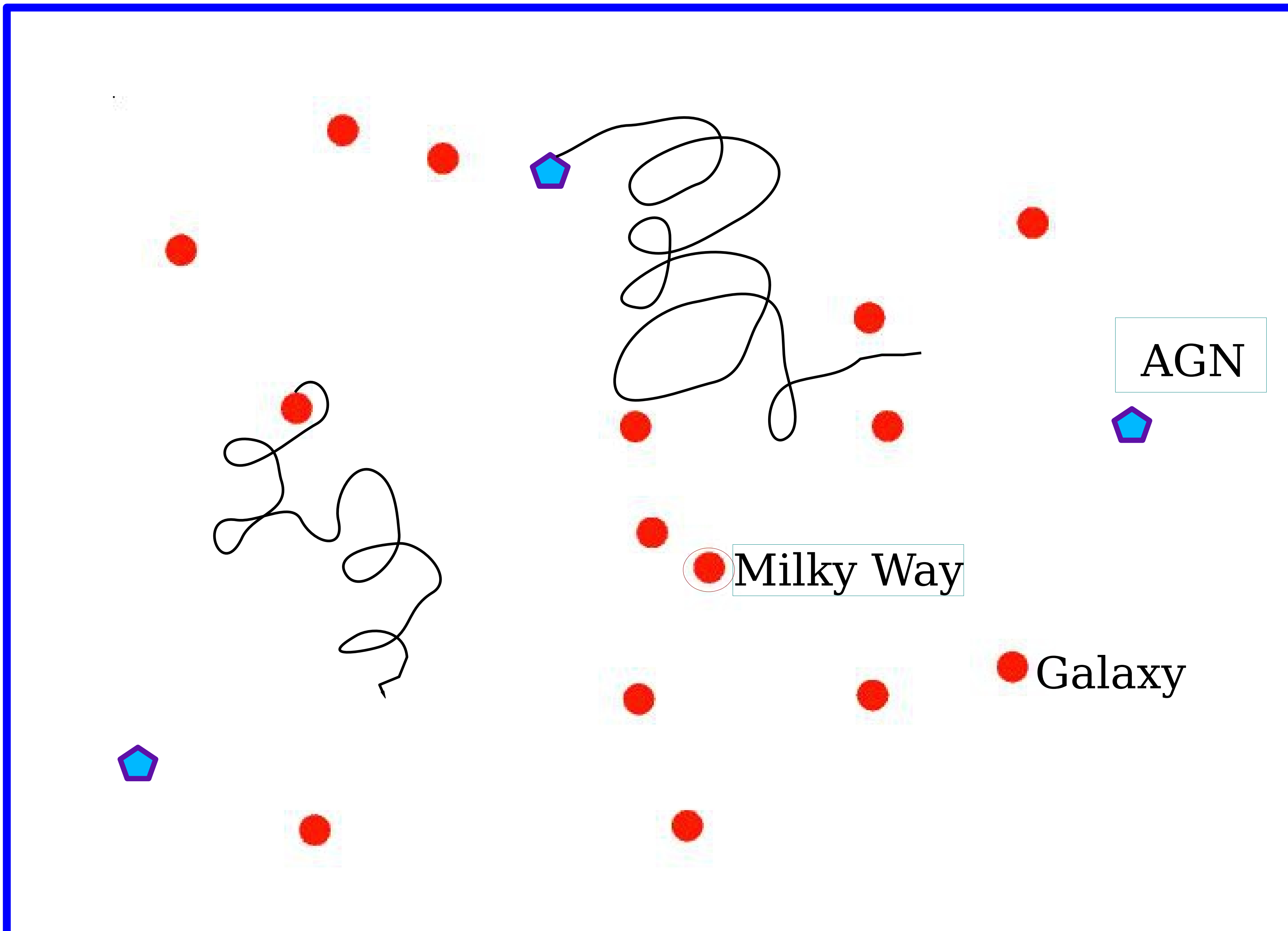
“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

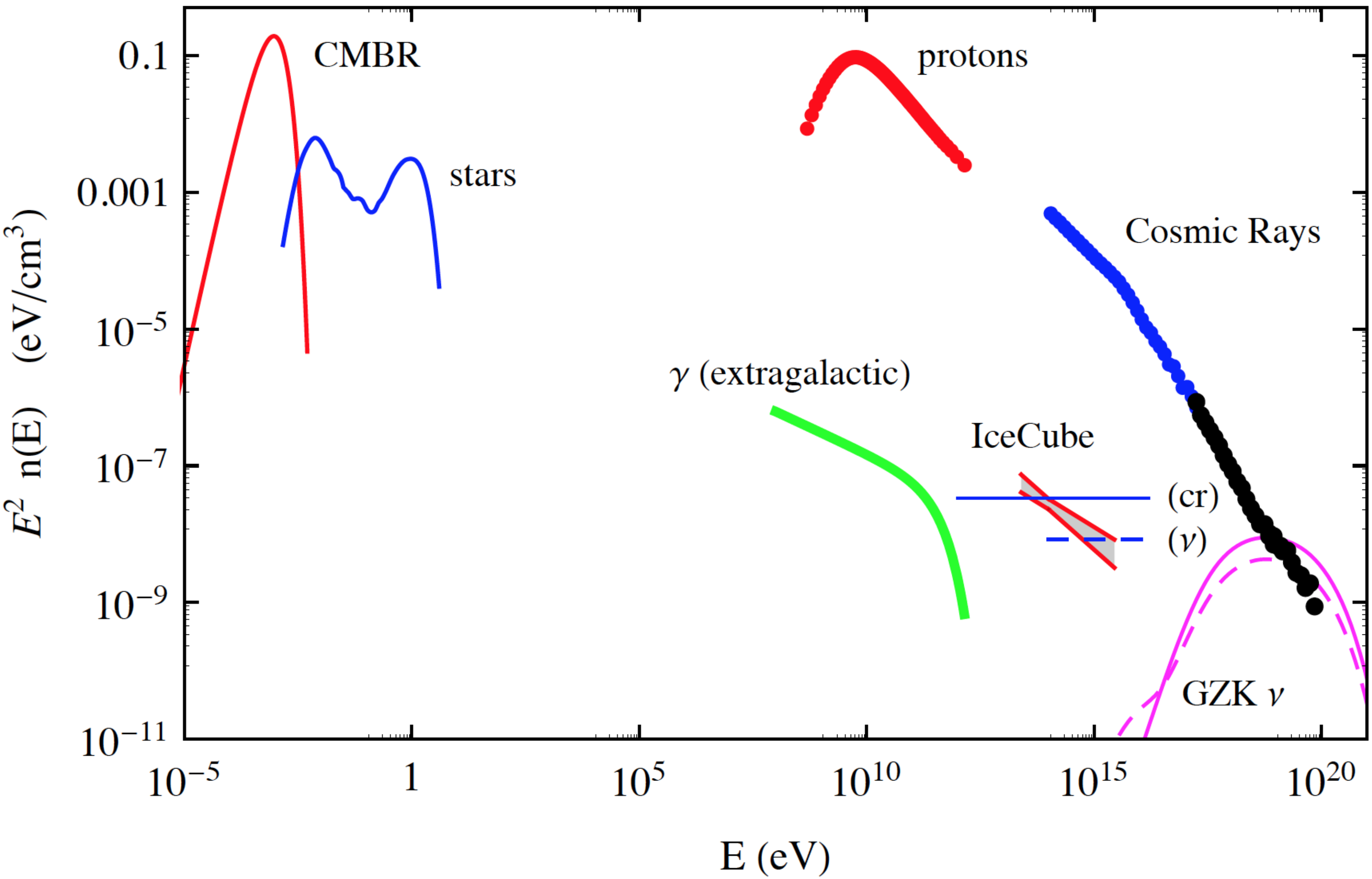
Space extension and properties of this “CR bubble” remain very uncertain



(high energy) Extra-galactic CR crossing the Galaxy.

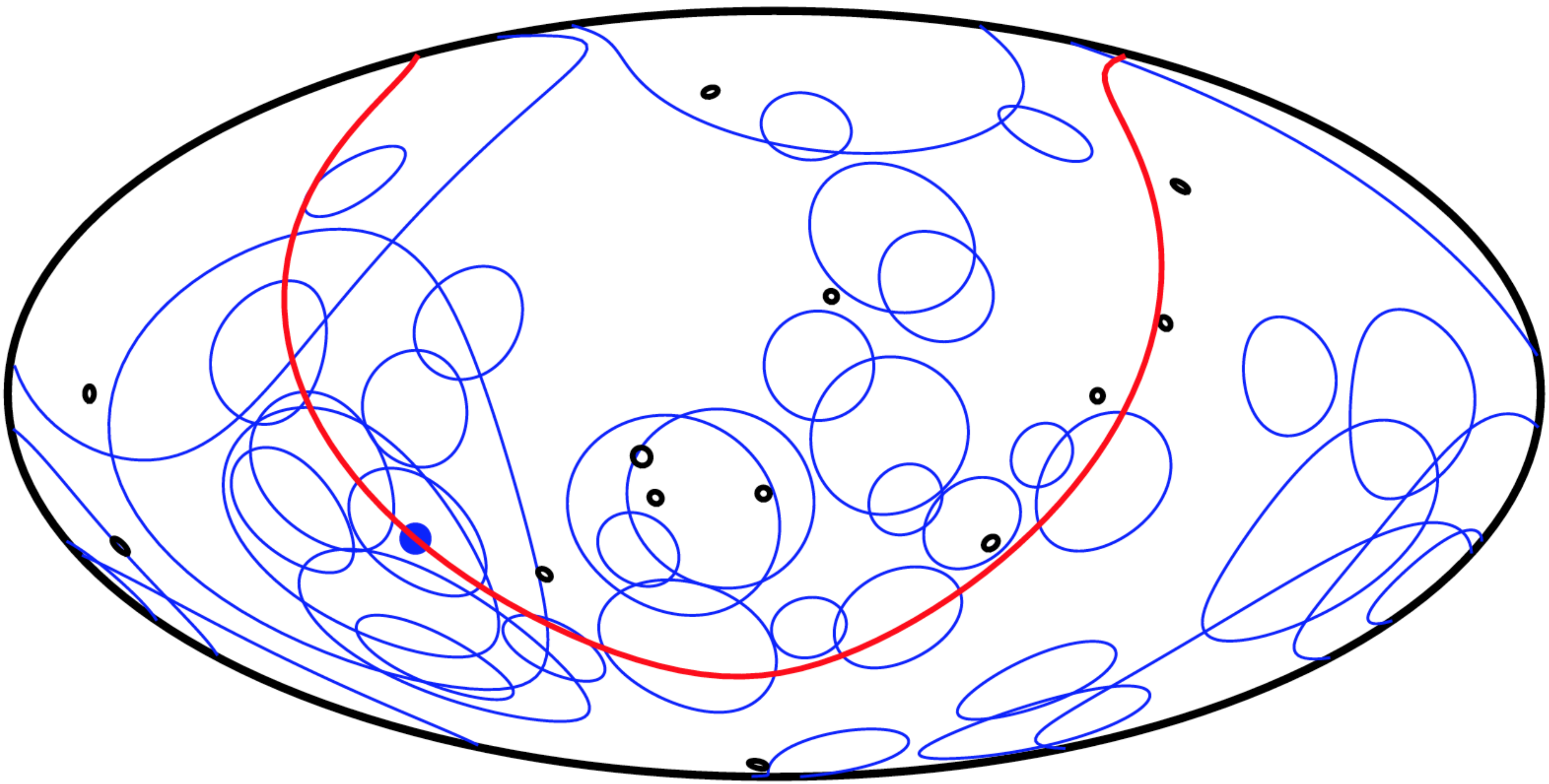
Piece of extragalactic space: Non MilkyWay-like sources



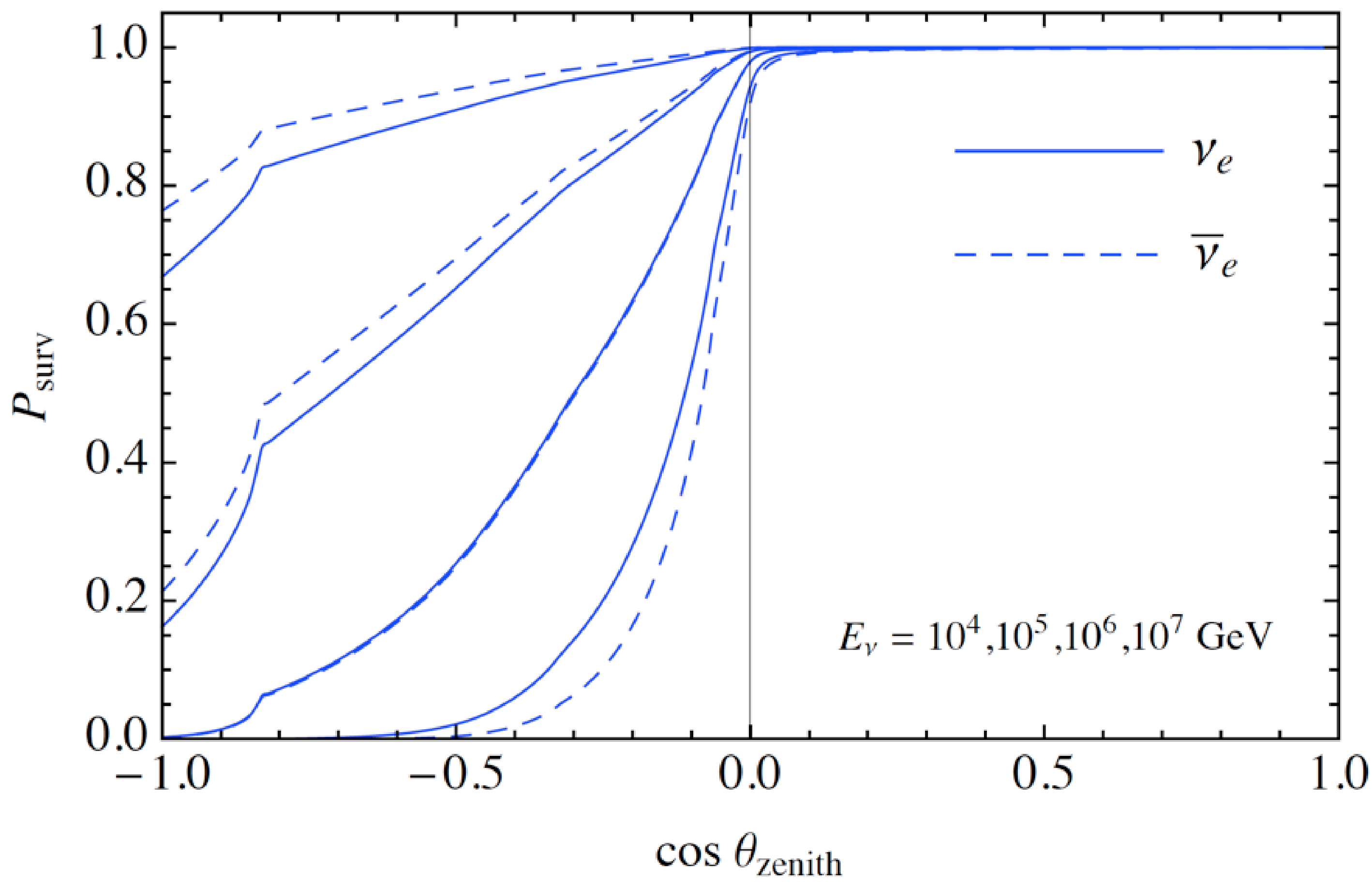


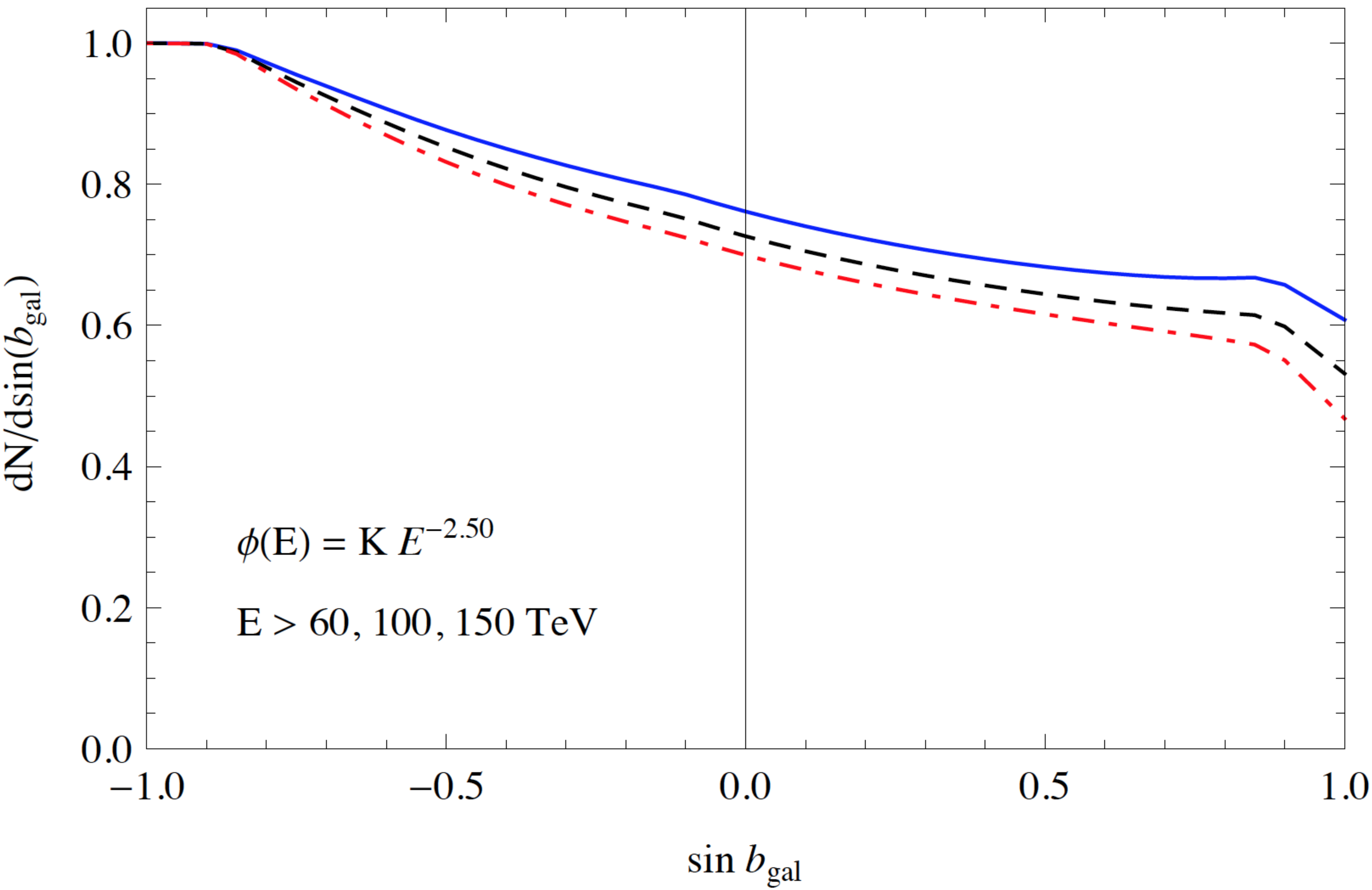
CMBR
stars
protons
Cosmic Rays
γ (extragalactic)
IceCube
(cr)
(ν)
GZK ν
0.1
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-5}
1
10^{5}
10^{10}
10^{15}
10^{20}
E (eV)
E^2 n(E) (eV/cm^3)

IceCube astrophysical neutrino signal

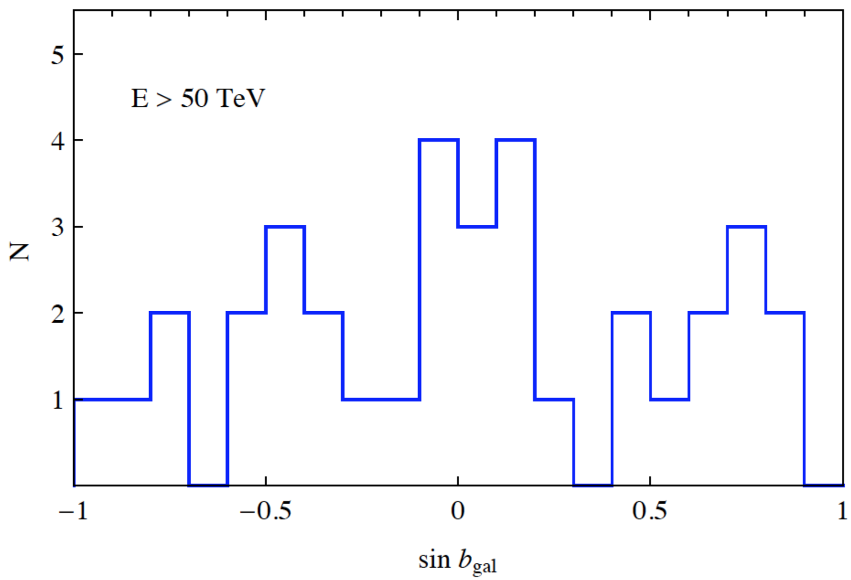


Effects of absorption on the angular distribution of the neutrinos

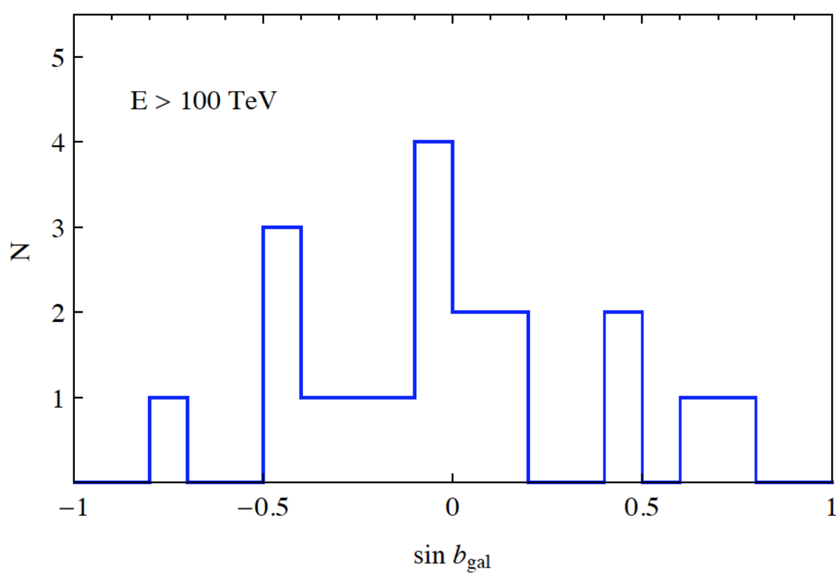


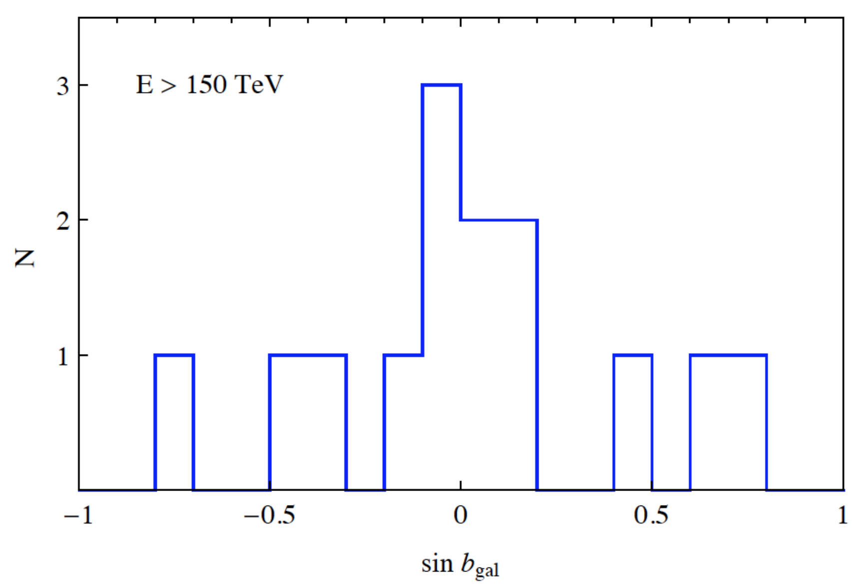


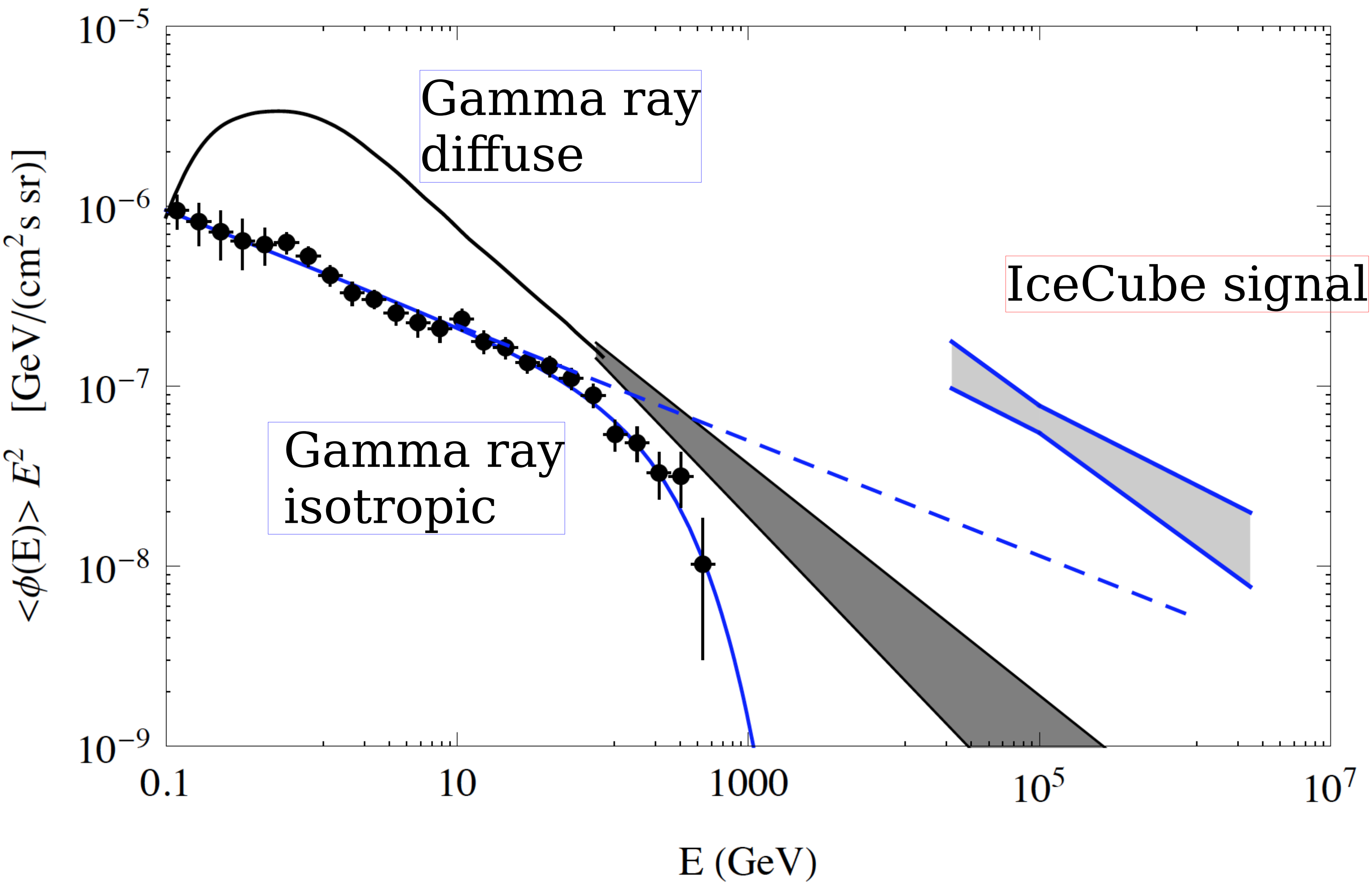
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0
dN/dsin(b_{gal})
sin b_{gal}
ϕ(E) = K $E^{-2.50}$
E > 60, 100, 150 TeV



Excess around the Galactic Disk ?

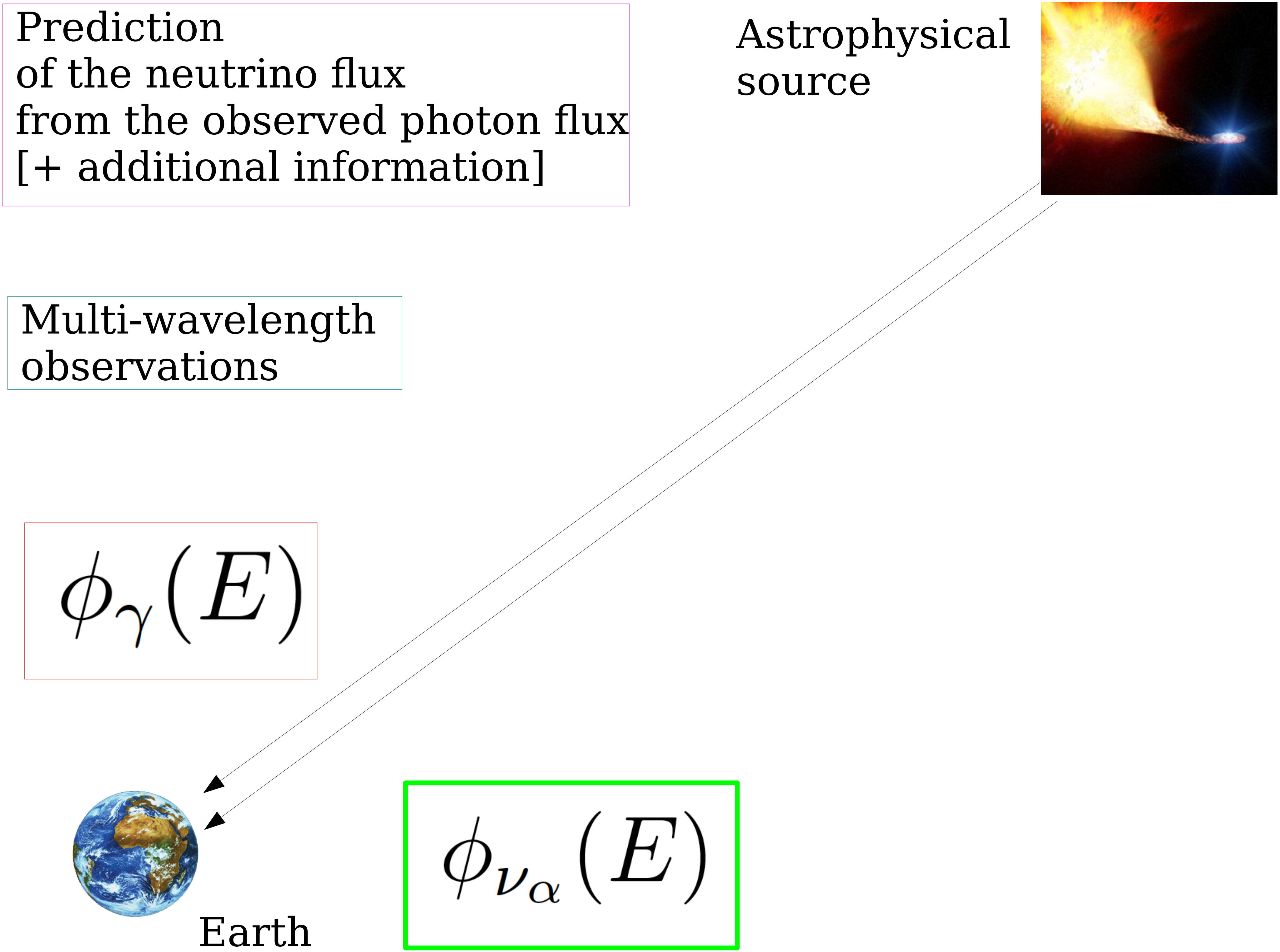




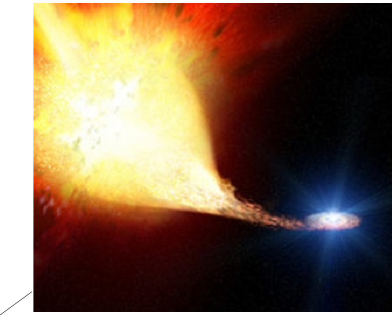


Gamma ray diffuse
IceCube signal
Gamma ray isotropic
$\langle\phi(E)\rangle E^2$ [GeV/(cm^{2}s sr)]
E (GeV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.1
10
1000
10^5
10^7

NEUTRINO POINT SOURCES


Prediction
of the neutrino flux
from the observed photon flux
[+ additional information]
Astrophysical
source
Multi-wavelength
observations
$\phi_\gamma(E)$
Earth
$\phi_{\nu_\alpha}(E)$

Astrophysical
source



$$\phi_{\gamma}^{\text{leptonic}}(E) + \phi_{\gamma}^{\text{hadronic}}(E)$$

Possible absorption in the source

Propagation effects (extragalatic)

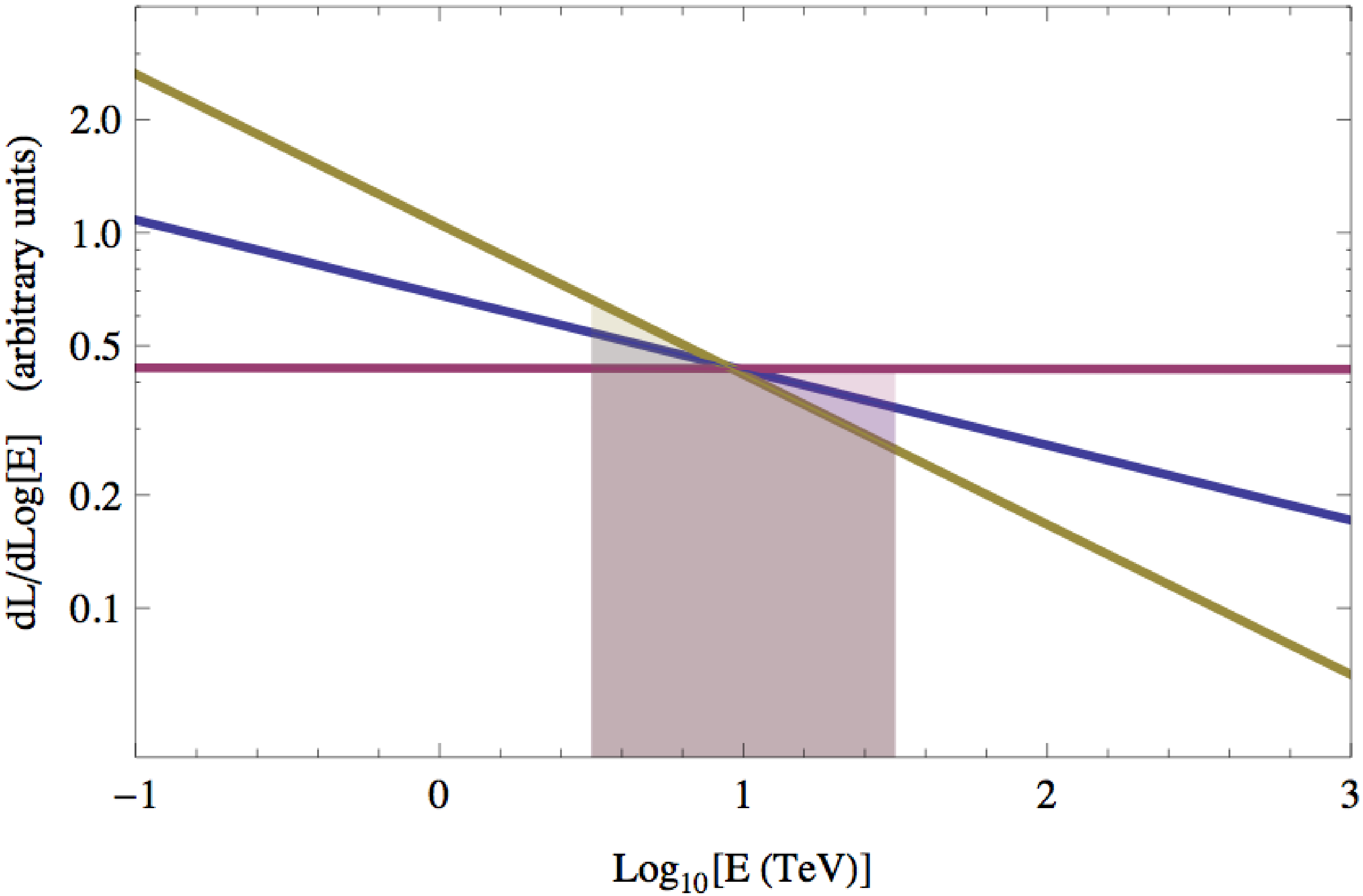
$$\phi_{\gamma}(E)$$

Flavor oscillations
(good theoretical control)

Earth

$$\phi_{\nu_\alpha}(E)$$

ENERGY
EXTRAPOLATION



“Standard Source”

$$\phi_\nu(E) = \frac{1}{4\,\pi\, r^2} \left[\frac{L^{\text{decade}}(E_*)}{\ln 10}\; E_*^{\alpha-2} \right] E^{-\alpha}$$

Table 3. Galactic sources.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	s[c]	Type	Association[d]
G1	02 40	+61 15	2.7	2.6	p	XRB	LSI+61 303
							E0241+6103
G2	05 35	+22 01	22–37	2.4–2.8	p	PWN	Crab nebula
G3	06 16	+22 31	0.6	3.1	p	SNR	IS443
G4	06 33	+05 21	0.9	2.5	p	UID	Monoceros?
							E0634-0521?
G5	08 35	−45 34	9	1.7, 3.4	e	PWN	Vela X
				1.5(14)			
G6	08 52	−46 20	21	2.1	m	SNR?	R0852-4622
G7	10 23	−57 45	4.5	2.5	e	UID	Westerlund2
					stellar cluster in H II region		
G8	13 02	−63 49	1.3	2.7	p	BP	P1259-63
G9	13 03	−63 11	4.3	2.4	e	UID	
G10	14 18	−60 58	2.6	2.2	e	PWN?	G313.3+0.1?
G11	14 20	−60 45	3.5	2.2	e	PWN?	P1420-6048?
							E1420-6038?
G12	14 28	−60 51	1.3	2.2	e	UID	
G13	14 42	−62 29	2.7	2,5	e	SNR	RCW86
G14	15 14	−59 09	5.7	2.3	e	PWN	MSH15-52
							P1509-58
G15	16 14	−51 49	8.1	2.5	e	UID	
G16	16 16	−50 53	6.7	2.4	e	PWN?	P1617-5055
G17	16 26	−49 05	4.9	2.2	e	UID	
G18	16 32	−47 49	5.3	2.1	e	UID	I16320-4751?
G19	16 34	−47 16	2.0	2.4	e	UID	I16358-4726?
							G337.2+0.1?
G20	16 40	−46 31	3.0	2.4	p	UID	G338.3-0.0?
							E1639-4702?
G21	17 02	−42 04	9.1	2.1	e	UID	P1702-4128?
G22	17 08	−41 04	2.7	2.5	p	UID	
G23	17 13	−38 11	0.7	2.3	e	UID	G348.7+0.3?
G24	17 13	−39 45	17	2.3	m	SNR	R1713.7-3946
			19	2.0(12)			G347.3-0.5?
G25	17 18	−38 33	0.3	0.7(6)	e	PWN?	
G26	16 32	−34 43	6.1	2.3	e	UID	

CRAB Nebula
SNR: RX 1713.7 -3946 (SN 393A)
SNR: R0952-4622 (Vela Junior)

Table 4. Galactic sources—continued.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	s[c]	Type	Association[d]
G27	17 45	−29 00	2.5	2.2	p	UID (Galactic Center)	
G28	17 45	−30 22	2.5	1.8	e	UID	E1744-3011?
G29	17 47	−28 09	0.8	2.4	p	SNR?	G0.9+0.1
G30	18 00	−24 00	1.9	2.5	e	SNR?	W28
			0.8	2.7	e	molecular cloud	
G31	18 04	−21 42	5.7	2.7	e	UID	G8.7-0.1
							P1803-2137?
G32	18 10	−19 18	4.6	2.2	e	PWN?	
G33	18 13	−17 50	2.7	2.1	p?	UID	G12.82-0.02?
G34	18 26	−13 44	20	2.4	m	PWN	G18.0-0.7
			21	2.2(25)			P1826-1334
G35	18 26	−14 49	1.9	2.1	p	XRB	LS 5039
			2.3/0.1	1.9/2.5	gamma ray flux varies with 3.9d		
G36	18 33	−10 33	0.5	2.1	p	SNR	G21.5-0.9
						PWN	P1833-1034
G37	18 34	−08 45	2.6	2.5	e	UID	G23.3-0.3
							W41?
G38	18 37	−06 56	5.0	2.3	e	UID	G25.5+0.0
G39	18 41	−05 33	12.8	2.4	e	UID	
G40	18 46	−02 59	0.6	2.3	p	SNR?	Kes75
					e	PWN?	P1846-0258
G41	18 57	+02 40	6.1	2.4	e	UID	
G42	18 58	+02 05	0.6	2.2	p?	UID	
G43	19 08	+06 30	8.8[h]	2.3	e	SNR?	G40.5-0.5
			3.2	2.1			
G44	19 12	+10 10			e	PWN?	P1913+1011?
G45	19 58	+35 12	2.3[g]	3.2	p	XRB	Cyg X-1
G46	20 19	+37 00	8.7[h]	2.3	e	PWN?	G75.2+0.1
G47	20 32	+41 30	0.6	1.9	e	UID	Cyg OB2?
			9.8[h]	2.3		?	
G48	23 23	+58 49	0.7	2.5	p?	SNR	Cas A

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.
[b] Spectral index Γ when fitted by $E^{-\Gamma}$. See text for details.
[c] p: point-like, e: extended. m: morphological structure studied.

GALACTIC TeV catalog

Table 5. Extragalactic sources.

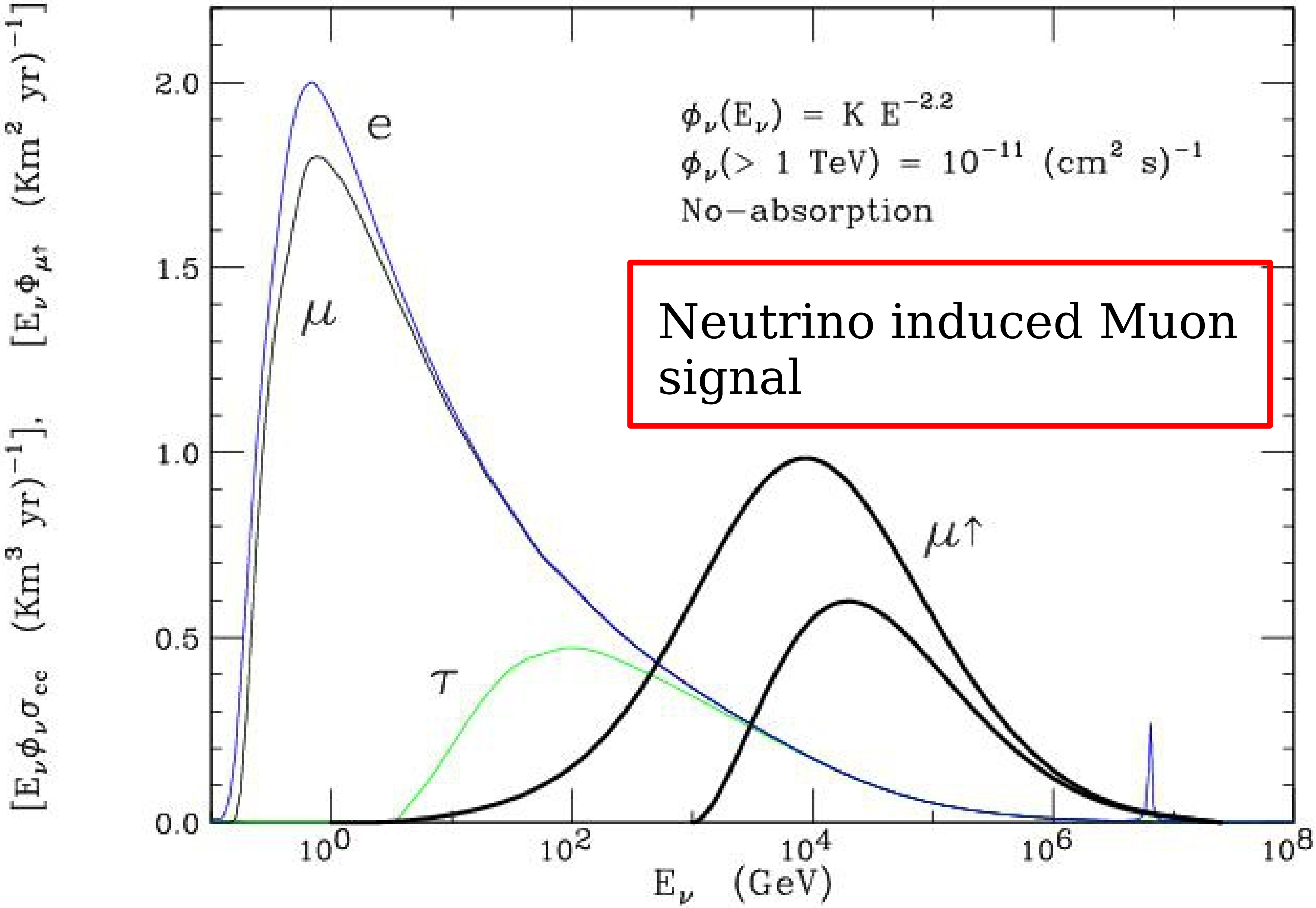
	RA	Dec	Flux[a]	Γ[b]	z[c]	Name
E1	02 32 53.2	+20 16 21	0.62	2.5	0.140	1ES 0229+200
E2	03 49 23.0	−11 58 38	0.45	3.1	0.188	1ES 0347−121
E3	05 50 40.8	−32 16 18	~0.3	2.8	0.069	PKS 0548-322
E4	10 15 04.1	+49 26 01	~0.3	4.0	0.212	1ES 1011+496
E5	s11 03 37.7	−23 29 31	0.4	2.9	0.186	1ES 1101−232
E6	11 04 27.6	+38 12 54	12–97	2.4–3.1(3)	0.031	Mkn 421
E7	11 36 26.4	+70 07 28	0.9	3.3	0.046	Mkn 180
E8	12 21 22.1	+30 10 37	1.3	3.0	0.182	1ES 1218+304
E9	12 30 54.4	+12 24 17	1	2.9	0.004	M87
E10	12 56 11.1	−05 47 22	[e]		0.536	3C279
E11	14 28 32.7	+42 40 20	1–2	2.6–3.7	0.129	H 1426+428
E12	15 55 43.2	+11 11 21	0.1–0.2	4.0	0.36?	PG1553+113
E13	16 53 52.1	+39 45 37	0.5–100	1.9–2.3(5)	0.034	Mkn 501
E14	19 59 59.9	+65 08 55	4–120	2.7–2.8 1.8(4–10)	0.047	1ES 1959+650
E15	20 09 29.3	−48 49 19	0.2	4	0.071	PKS 2005-489
E16	21 58 52.7	−30 13 18	2–3	3.3–3.4	0.116	PKS 2155-304
E17	22 02 43.3	+42 16 40	~0.3	3.6	0.069	BL Lacetae
E18	23 47 06.0	+51 42 30	1–5	2.3–2.5	0.044	1ES 2344+514
E19	23 59 07.9	−30 37 41	~0.3	~3.1	0.165	H 2356−309

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.

[b] Spectral index Γ when fitted by $E^{-\Gamma}$.

[c] Red shift.

extra-GALACTIC TeV catalog



$$\Phi_{\mu\uparrow} \simeq (1 \div 5) \left[\frac{\phi_\nu(\geq 1\ \mathrm{TeV})}{10^{-11}\ (\mathrm{cm}^2\,\mathrm{s})^{-1}} \right]\ (\mathrm{Km}^2\ \mathrm{yr})^{-1}$$

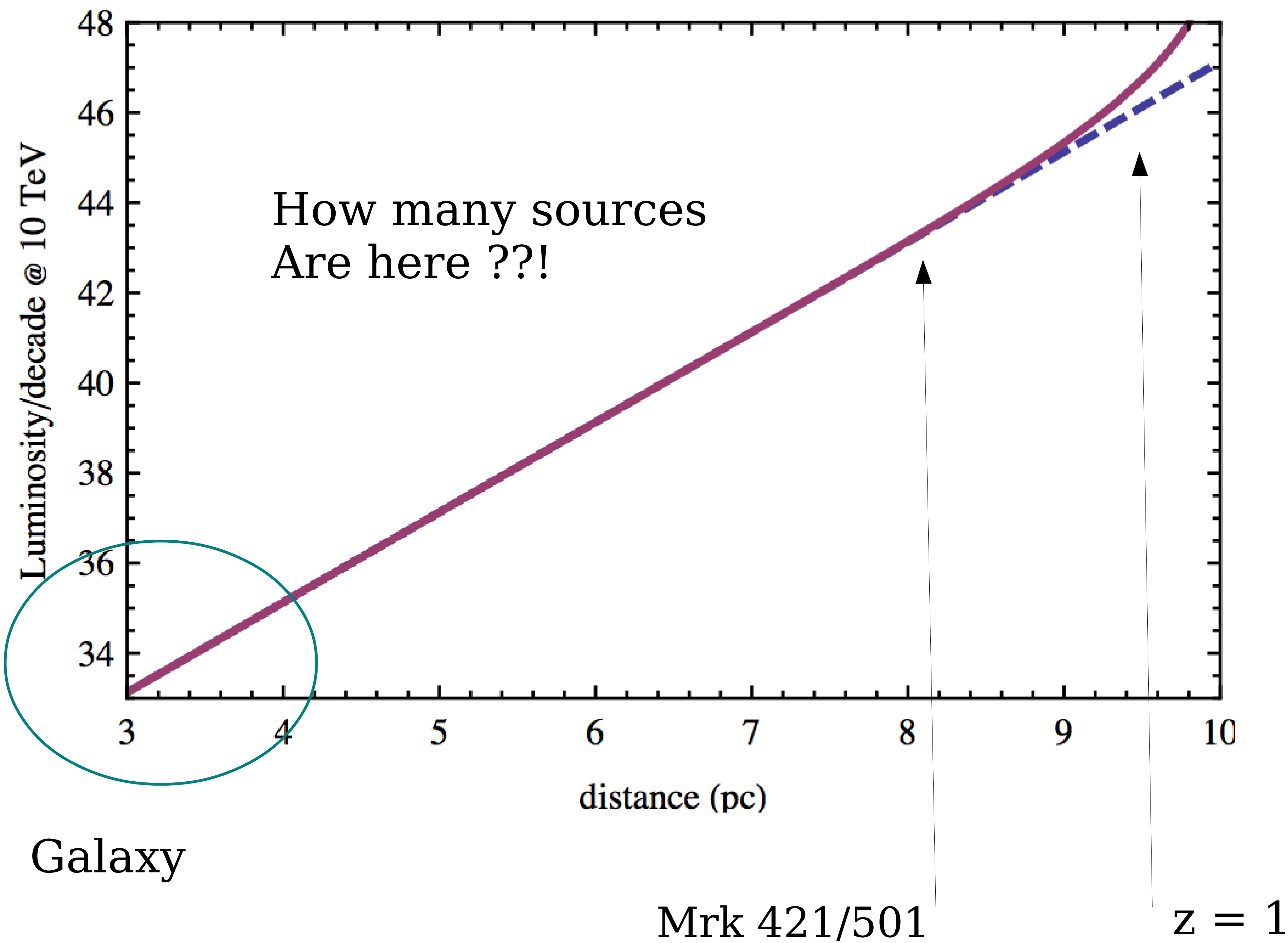
Energy Response: Peak @ 20 TeV

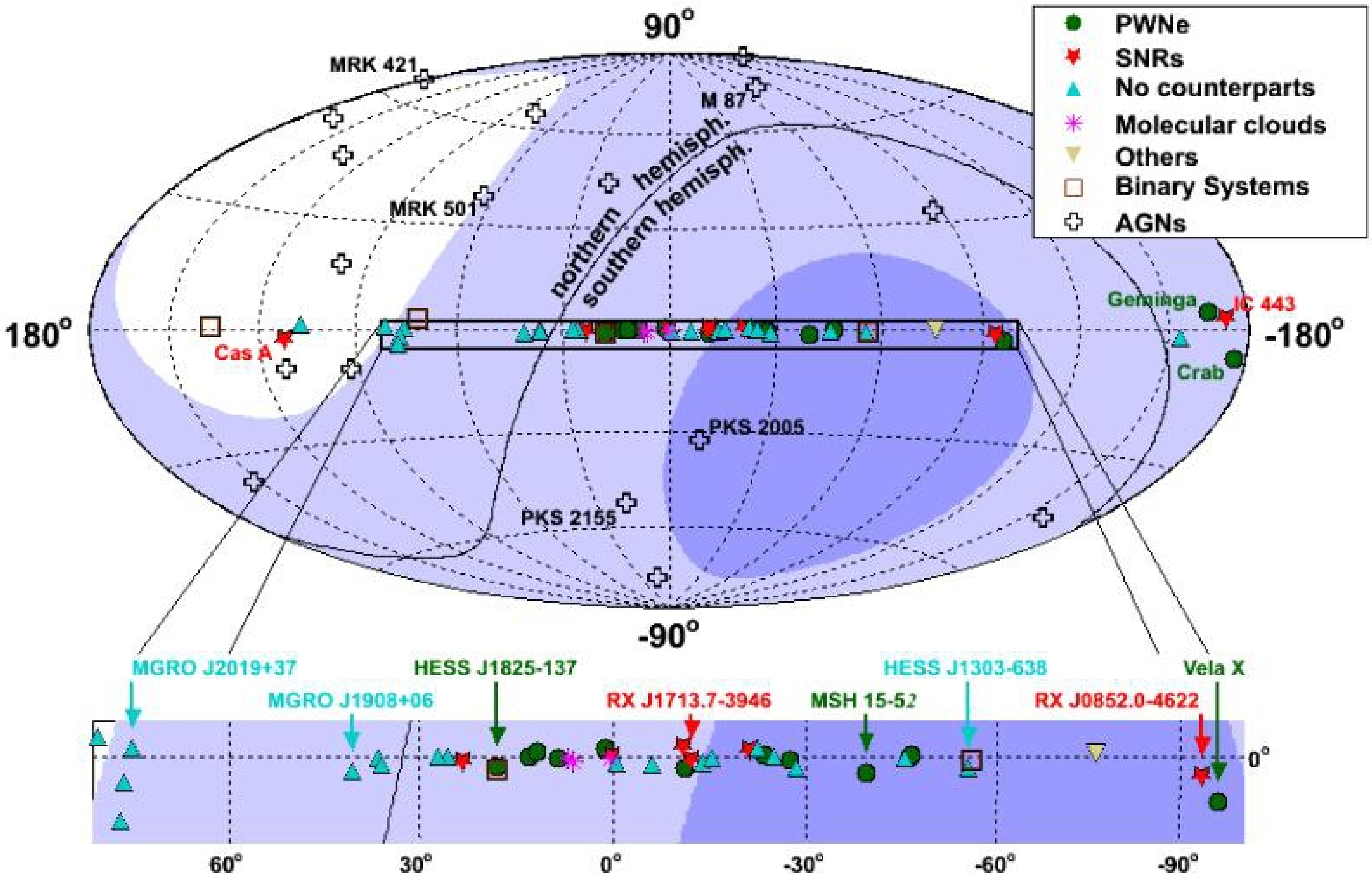
From the Neutrino Flux to the Muon induced signal.

$$N_{\mu\uparrow} \simeq 7.5 \times \left(\frac{L}{10^{34}\ \mathrm{erg/s}}\right) \left(\frac{\mathrm{Kpc}}{r}\right)^2 \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right)$$

$$N_{\mu\uparrow} \simeq 0.4 \times \left(\frac{L}{10^{46}\ \mathrm{erg/s}}\right) \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right) \frac{1}{z^2}$$

Line : 1 (muon event)/(km2 yr)





90°
-90°
180°
-180°
PWNe
SNRs
No counterparts
Molecular clouds
Others
Binary Systems
AGNs
MRK 421
M 87
MRK 501
northern hemisph.
southern hemisph.
Geminga
IC 443
Cas A
Crab
PKS 2005
PKS 2155
MGRO J2019+37
HESS J1825-137
HESS J1303-638
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
60°
30°
0°
-30°
-60°
-90°

TeV Galactic Sources
Measured by HESS, MAGIC

Have FLUX:
Flux (E_g > 1 TeV) = 0.11 - 2.1

UNIT : $10^{-11}\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$

Three Brightest sources in the TeV sky:

CRAB NEBULA

2 young SNR
Vela Junior
RX 1713.7-3946

$$\boxed{\Phi(E > 1\ \mathrm{TeV}) \simeq 10^{-11}\ (\mathrm{cm}^2\,\mathrm{s})^{-1}}$$

TeV Photons in a Cherenkov Telescope

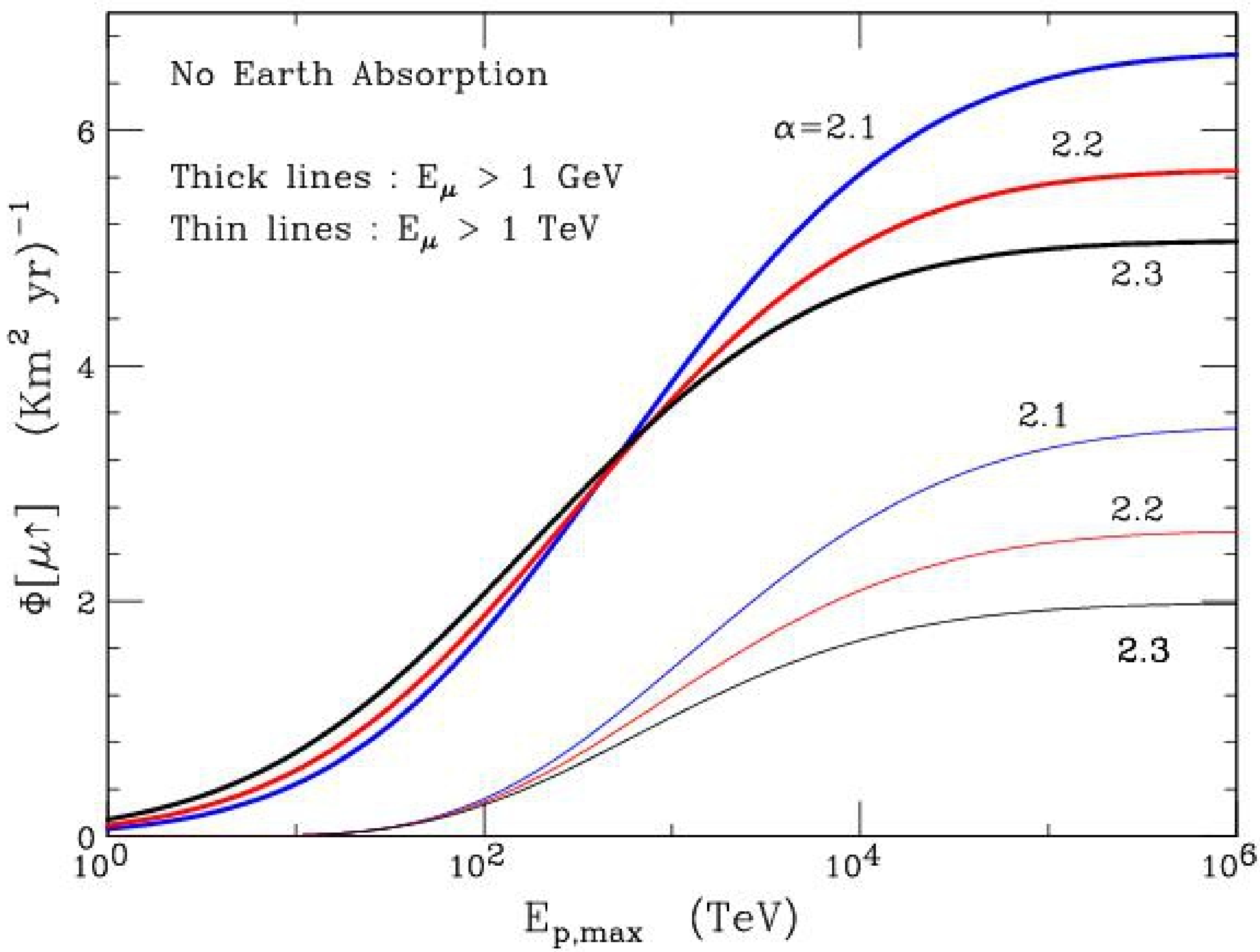
$$\sim 10\ \frac{\mathrm{events}}{\mathrm{hour}}$$

$$\phi(E) \propto E^{-2}$$

Up-going muons Neutrino telescope

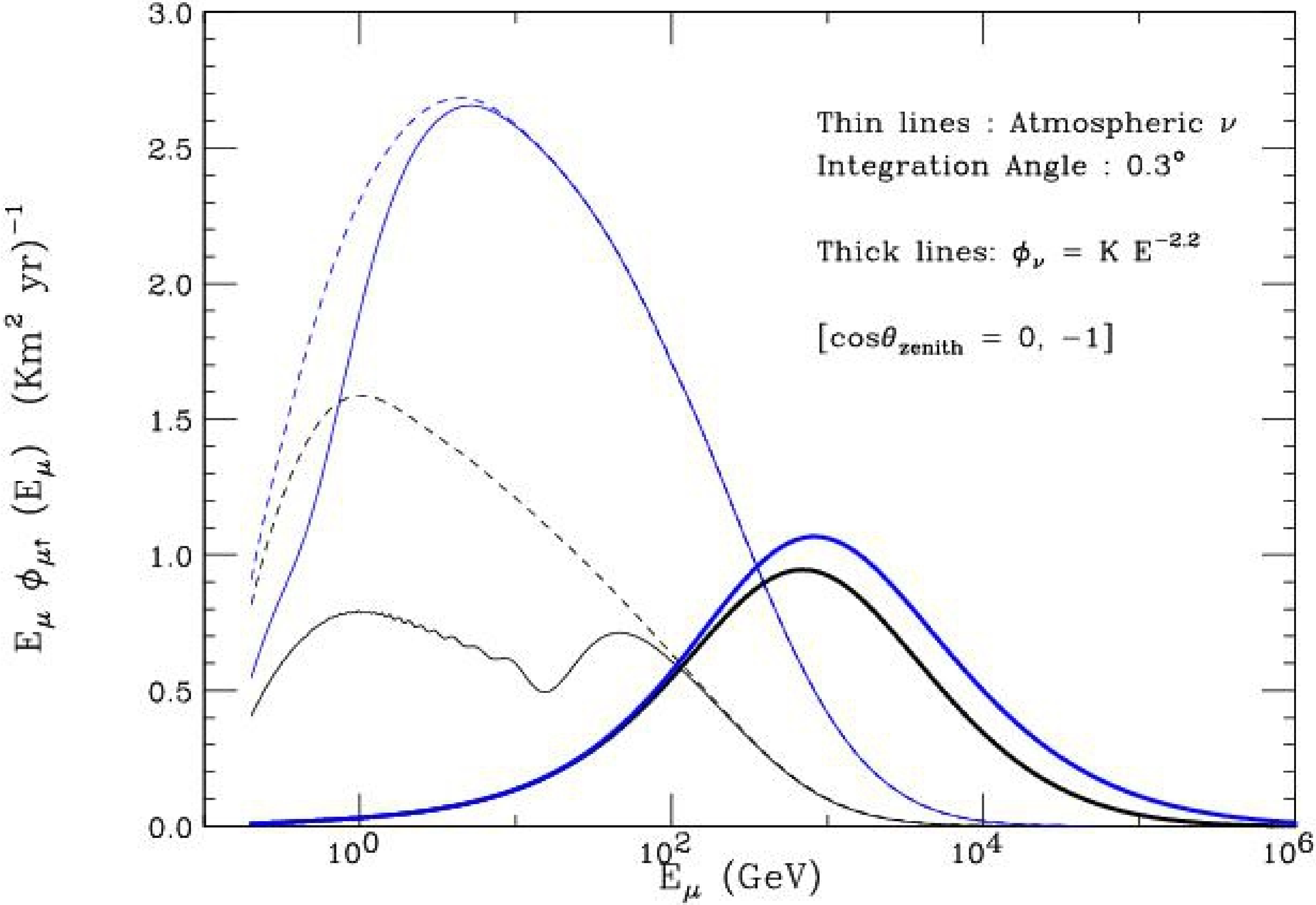
$$\sim 2\ \frac{\mathrm{events}}{\mathrm{Km}^2\,\mathrm{yr}}$$

Importance of cutoff !!

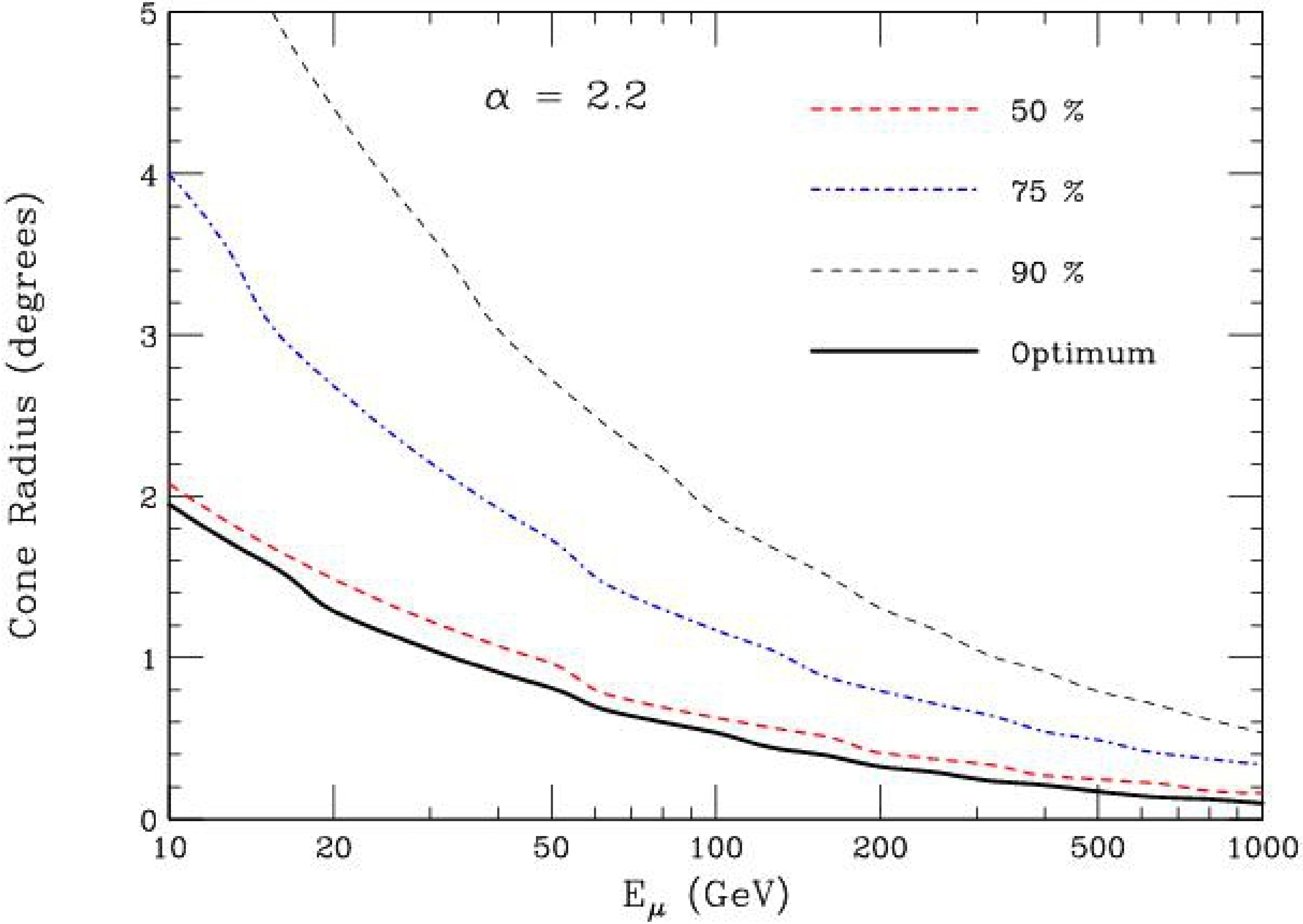


BACKGROUND

Atmospheric Neutrinos



Angular Distribution of the Neutrino – induced Muons



IF TEV emission of the
Brightest TeV sources
is of hadronic nature

detection with neutrinos
is within reach .....

Few events / (km2 yr)

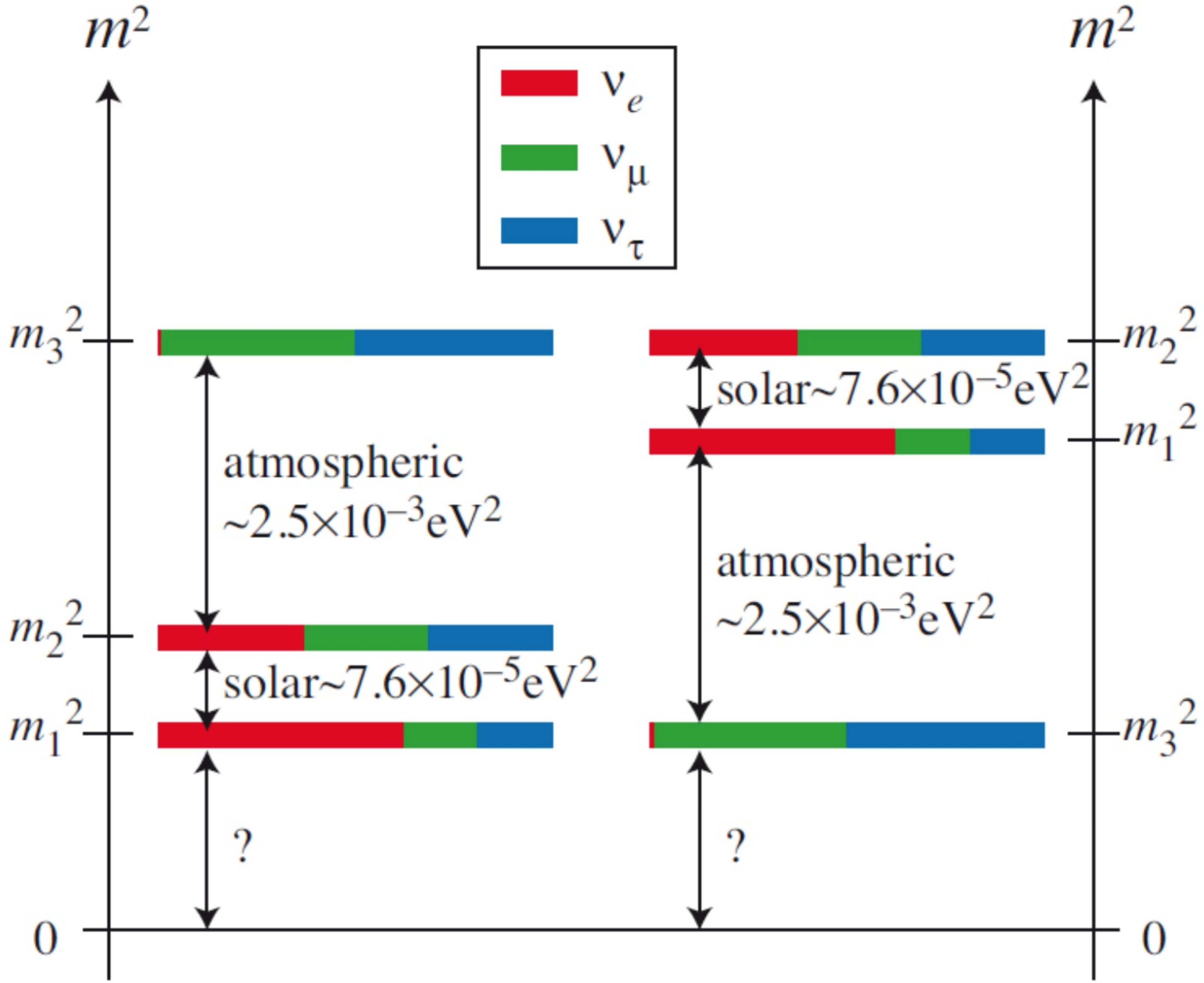
...but

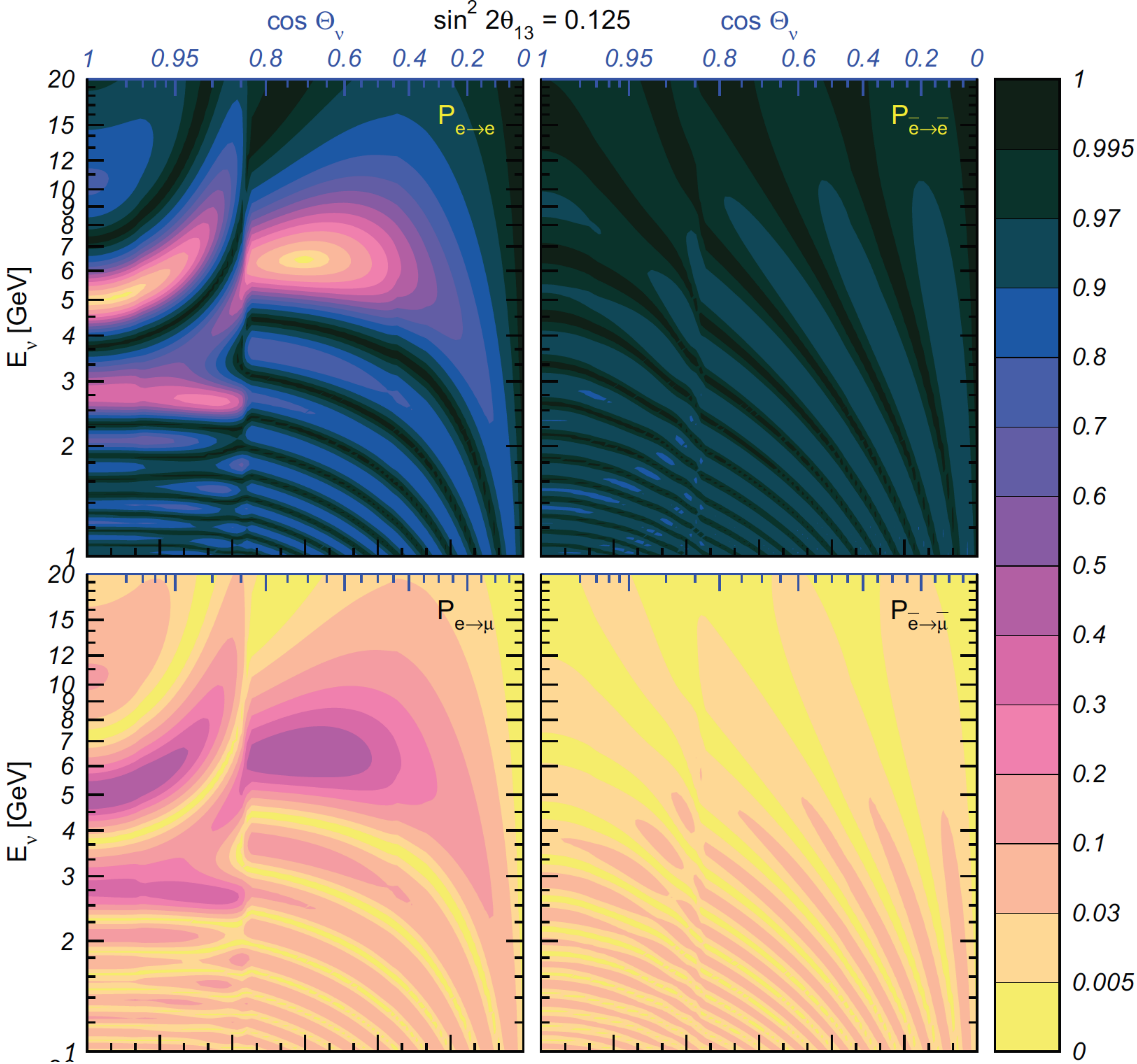
NOT EASY !

7. Outlook

- Neutrino Oscillations
- Dark Matter studies
- What can we learn with neutrinos that we cannot learn with gamma rays ?

Neutrino Mass Hierarchy:





cos Θ_ν
$\sin^2 2\theta_{13} = 0.125$
cos Θ_ν
1 0.95 0.8 0.6 0.4 0.2 0
$P_{e\to e}$
$P_{\bar{e}\to\bar{e}}$
$P_{e\to\mu}$
$P_{\bar{e}\to\bar{\mu}}$
E_ν [GeV]
20 15 12 10 9 8 7 6 5 4 3 2 1
1 0.995 0.97 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.03 0.005 0

Electro-neutrino event rate rate:

$$S_e^{(\text{no osc})} = \phi_{\nu_e}\ \sigma_{\nu_e}$$

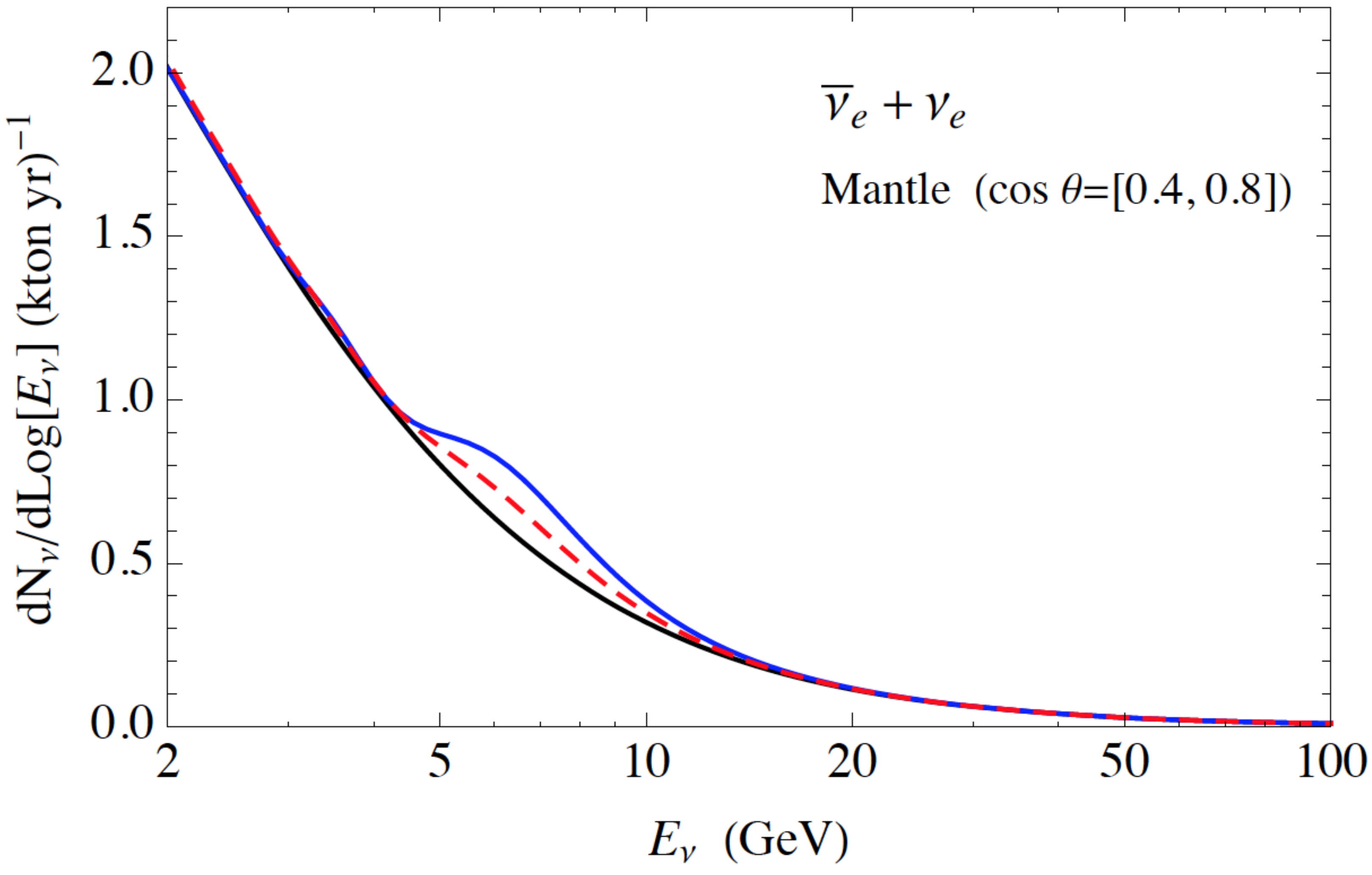
$$S_e = \left[\phi_{\nu_e}\ P_{\nu_e\to\nu_e} + \phi_{\nu_\mu}\ P_{\nu_\mu\to\nu_e}\right]\ \sigma_{\nu_e}$$

$$S_{\overline{e}}^{(\text{no osc})} = \phi_{\overline{\nu}_e}\ \sigma_{\overline{\nu}_e}$$

$$S_{\overline{e}} = \left[\phi_{\overline{\nu}_e}\ P_{\overline{\nu}_e\to\overline{\nu}_e} + \phi_{\overline{\nu}_\mu}\ P_{\overline{\nu}_\mu\to\overline{\nu}_e}\right]\ \sigma_{\overline{\nu}_e}$$

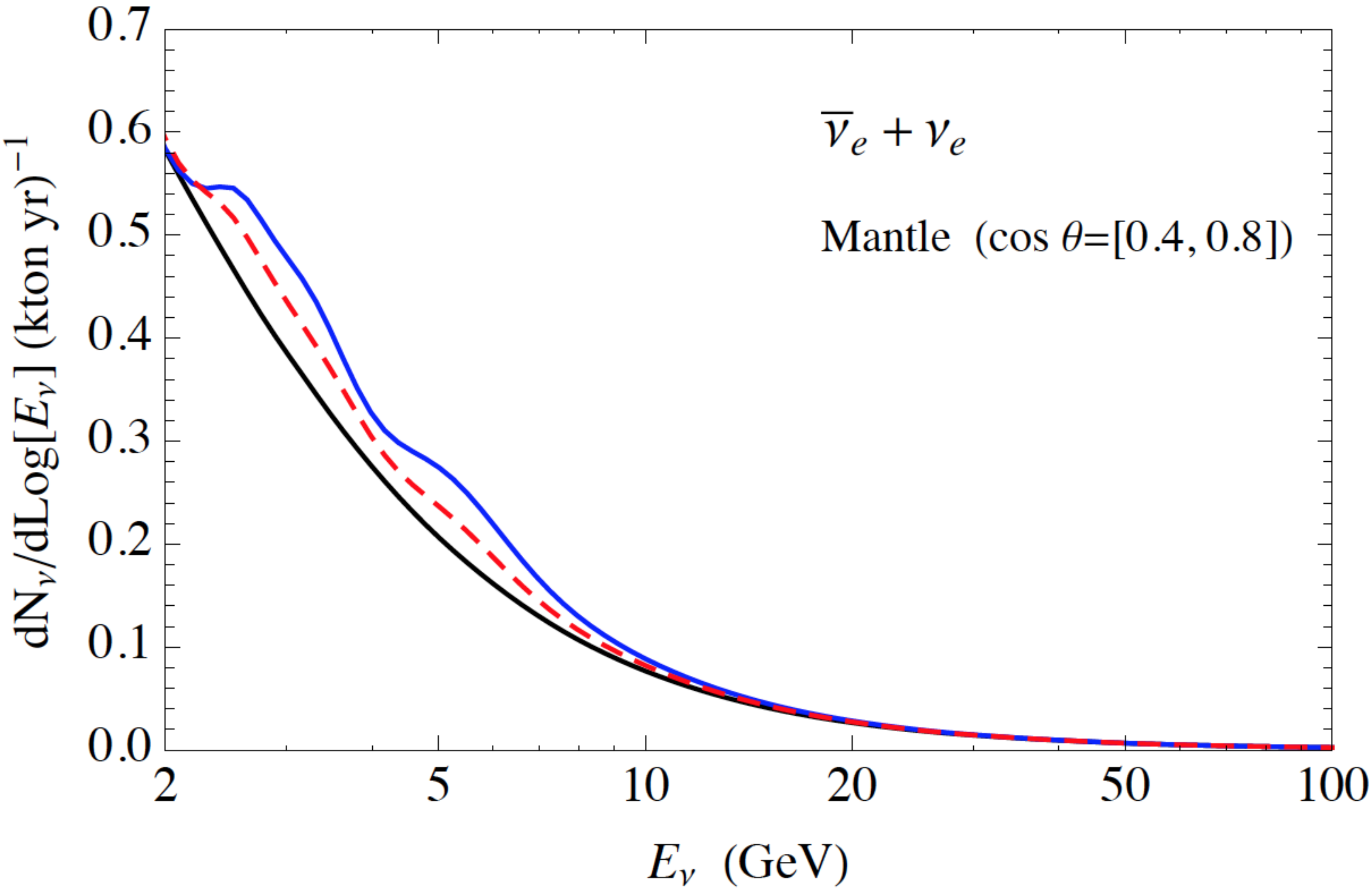
Sum: Electron Neutrinos + Anti-neutrinos

[Large excess : Normal Mass hierarchy
Small excess : Inverse Mass hierarchy

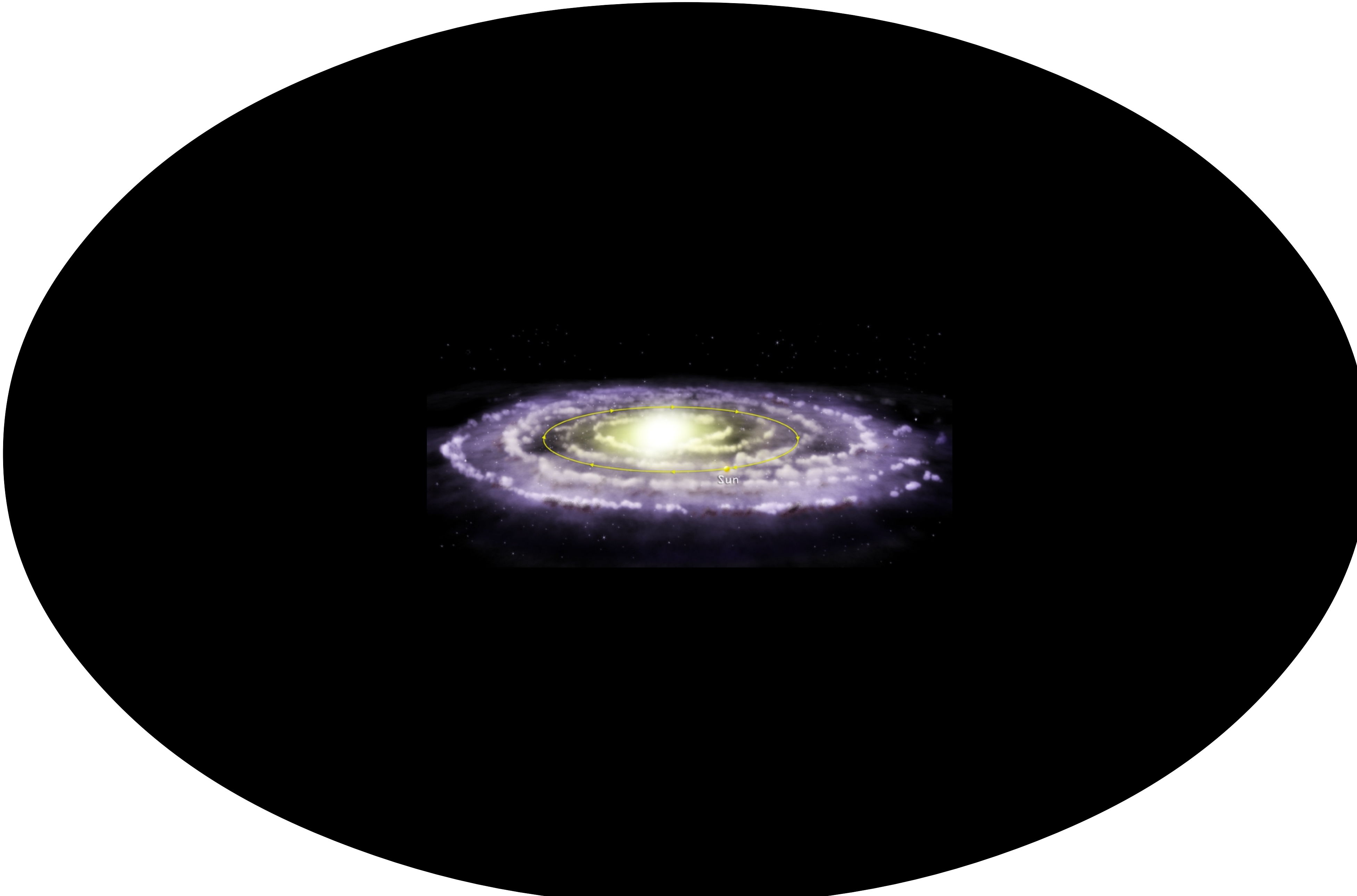


Sum: Electron Neutrinos + Anti-neutrinos

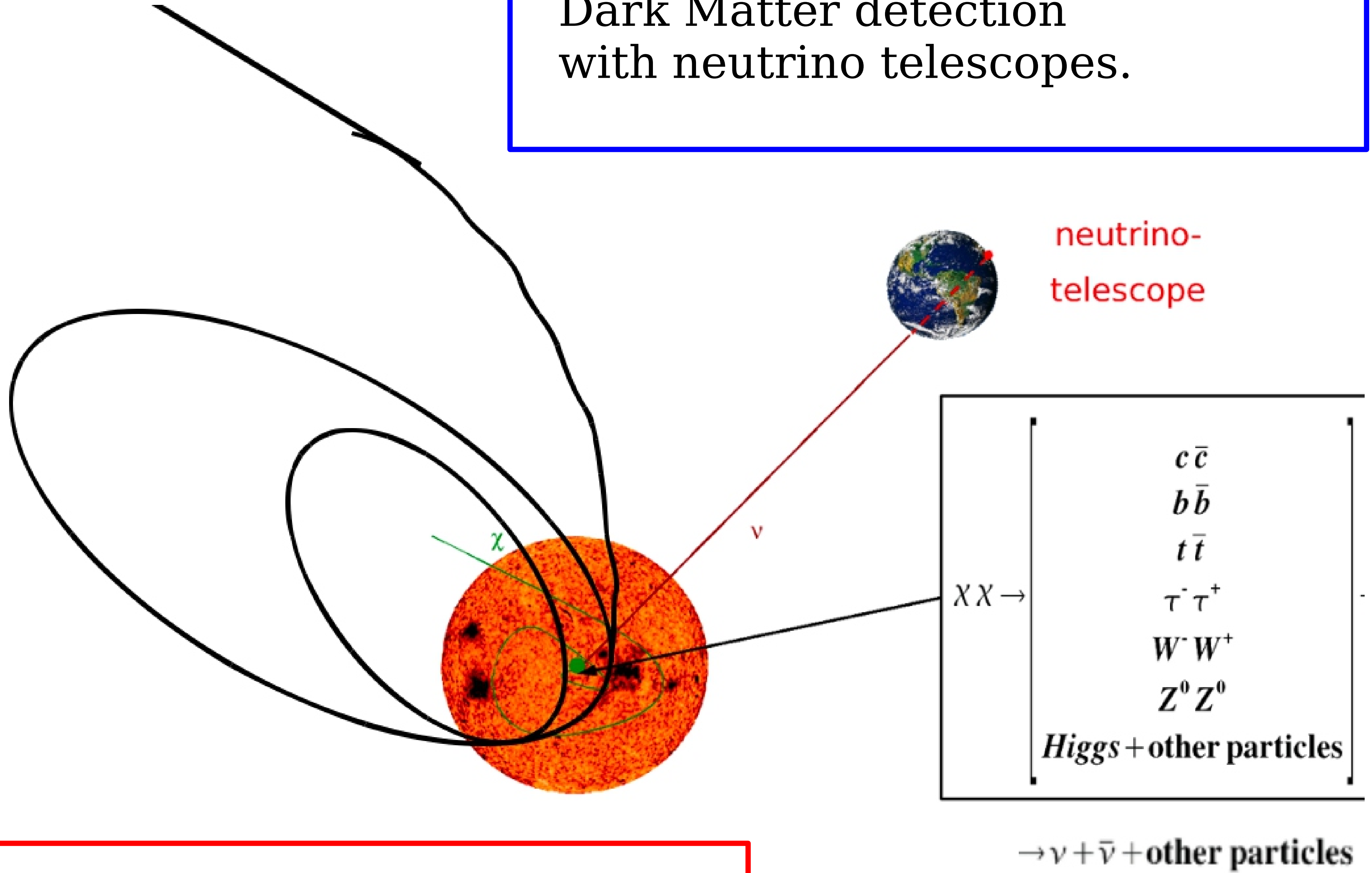
[Large excess : Normal Mass hierarchy
Small excess : Inverse Mass hierarchy



Indirect searches for
DARK MATTER



Dark Matter detection
with neutrino telescopes.



Accretion of DM
Particles in the Sun (and Earth)

Number of neutrinos in the sun

$$\frac{dN}{dt} = C_c - C_a N^2$$ = Capture Rate - Annihilation Rate

$$\boxed{\begin{aligned} N(t) &= \sqrt{\frac{C_c}{C_a}} \tanh\left\{\frac{t}{\tau_c}\right\} \\ \tau_c &\equiv (C_c C_a)^{-1/2} \end{aligned}}$$

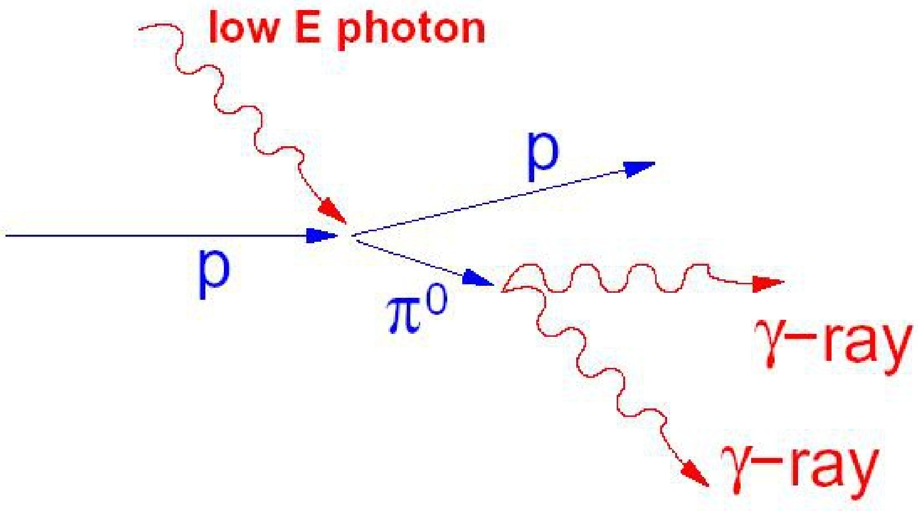
$$\xrightarrow{t \gg \tau_c} \sqrt{\frac{C_c}{C_a}}$$

$$t = t_\odot = 4.6 \ \mathrm{Gyr}$$

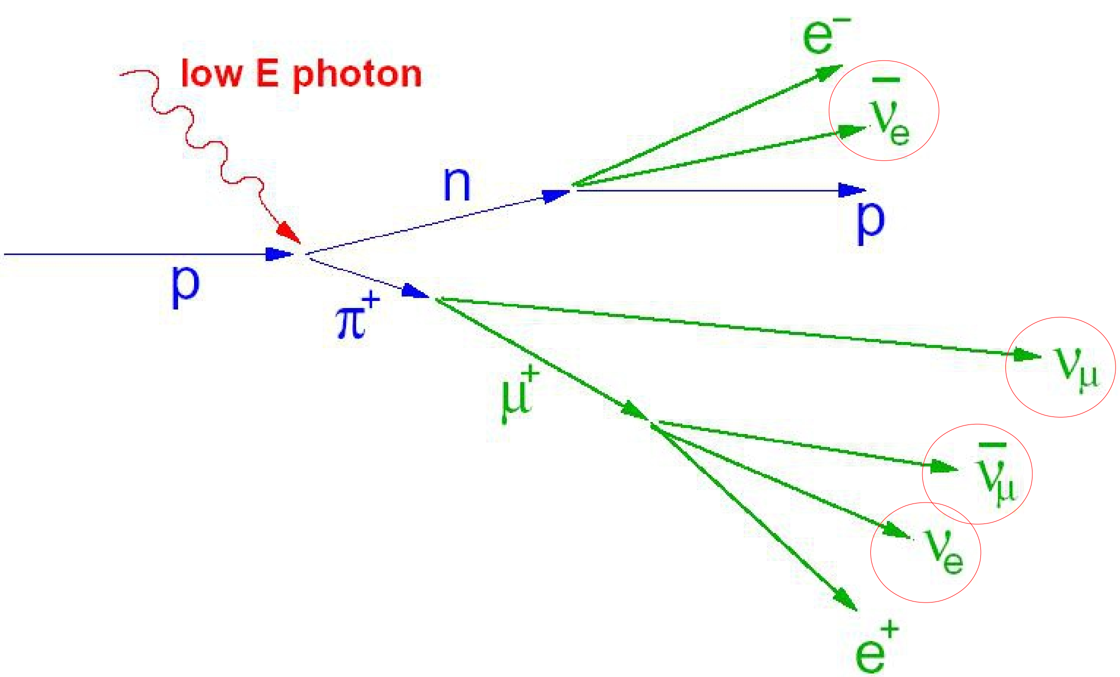
$$\tau_{c,\odot} \approx 10^8 \ \mathrm{yr}$$

$$\boxed{\Gamma_a(t) = \frac{C_c}{2} \tanh^2\left\{\frac{t}{\tau_c}\right\} \xrightarrow{t \gg \tau_c} \frac{C_c}{2}}$$ Annihilation Rate

Energy Loss Mechanisms for Protons:

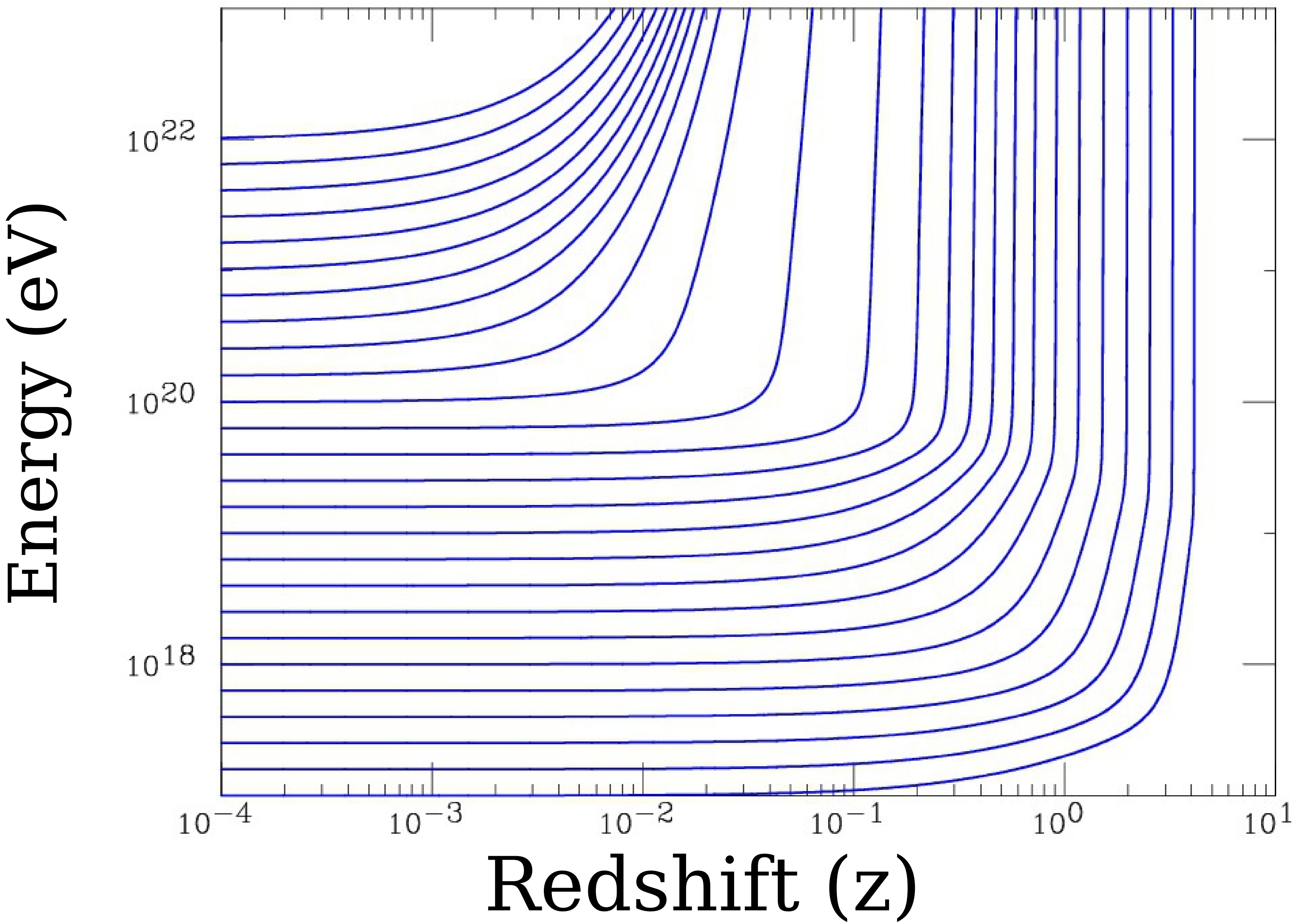


Greisen-Zatsepin- Kuzmin (GZK) suppression

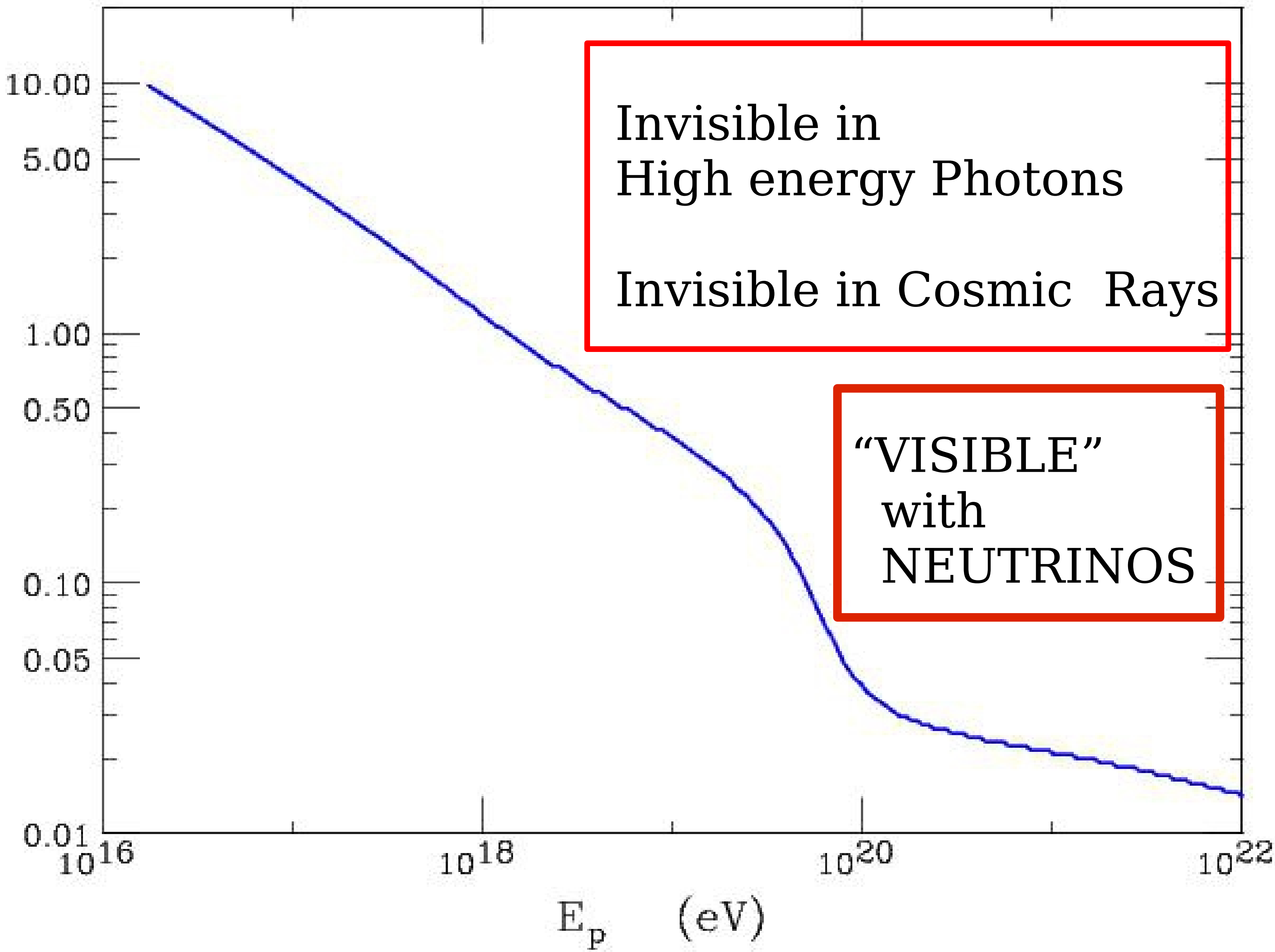


NEUTRINO PRODUCTION

Proton Energy Evolution with Redshift

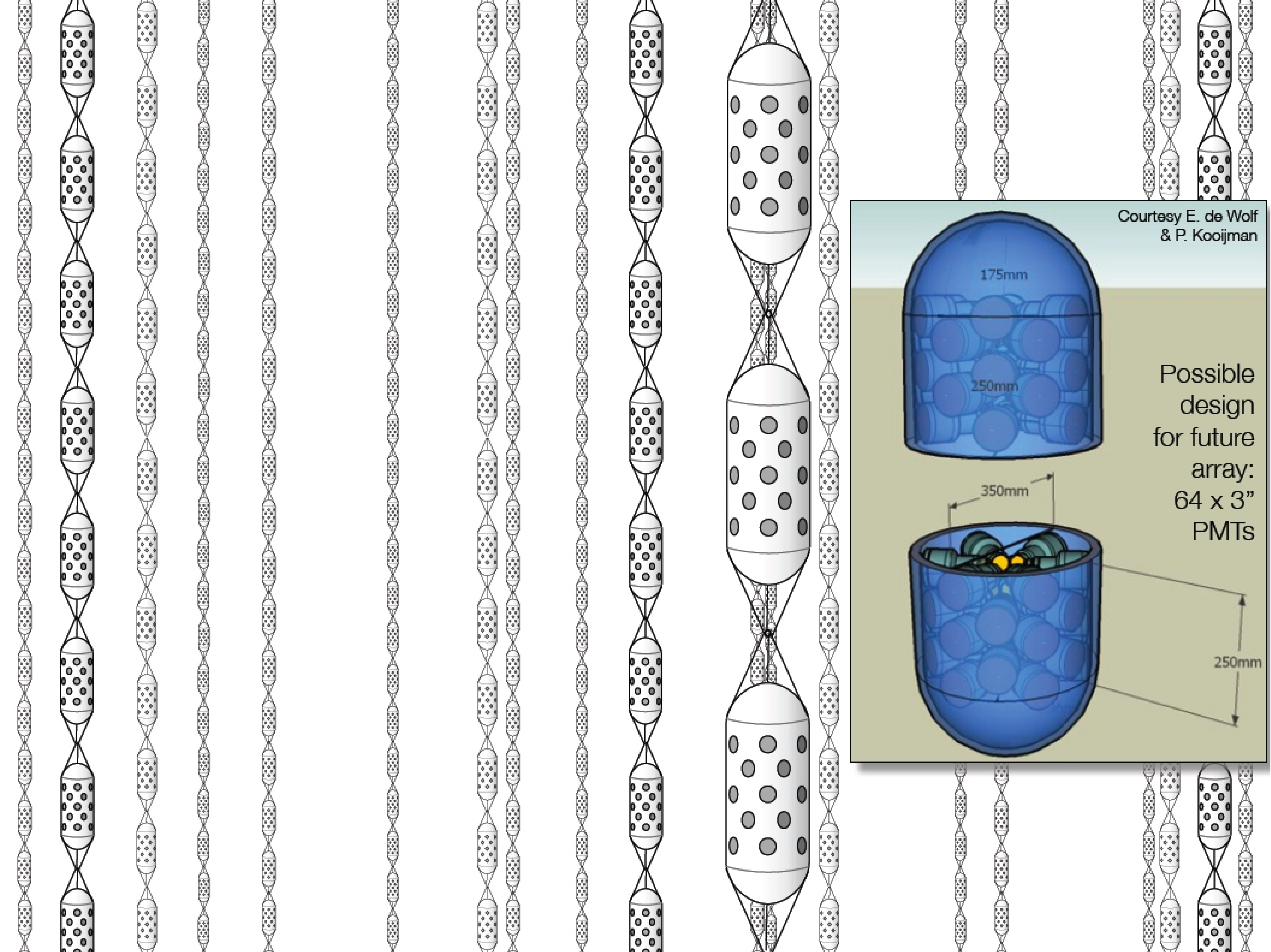


High Energy Proton Horizon



Neutrino Astronomy: beyond the “Km3 concept”

Radio, Acoustic,.....


Courtesy E. de Wolf
& P. Kooijman
175mm
250mm
350mm
250mm
Possible design for future array: 64 x 3" PMTs

Radio Detection of neutrinos

ANITA-II over Antarctica

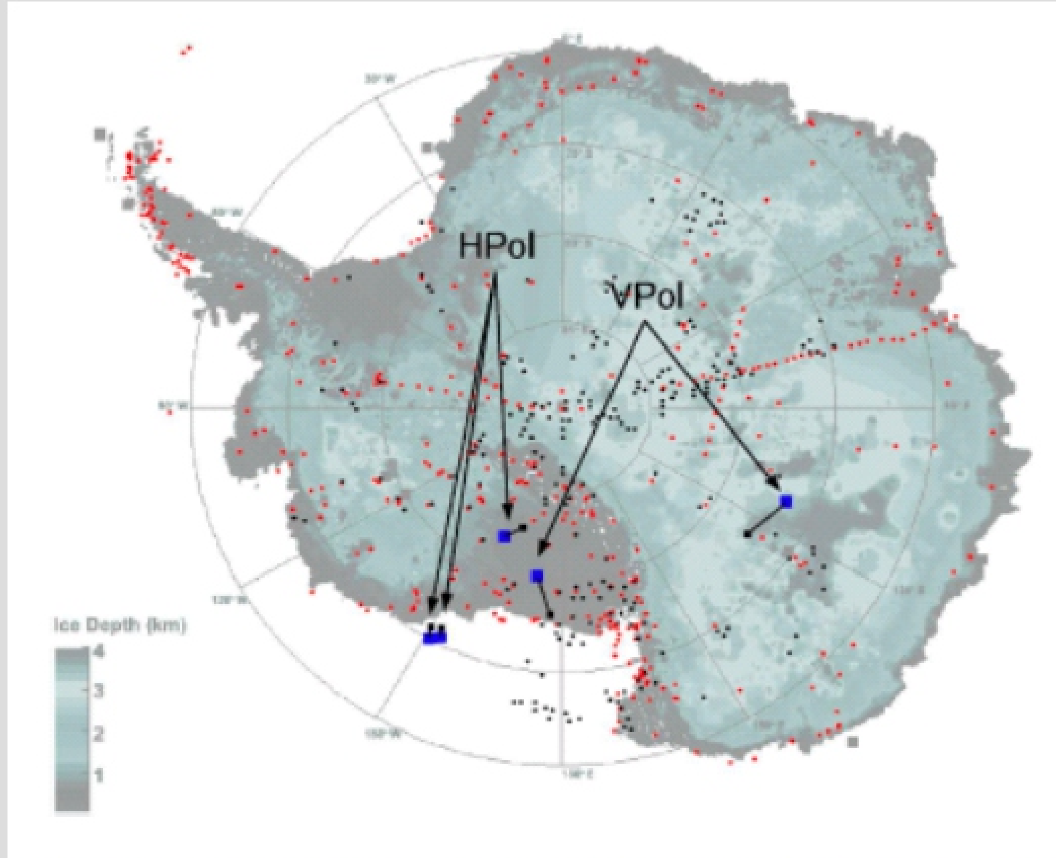


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

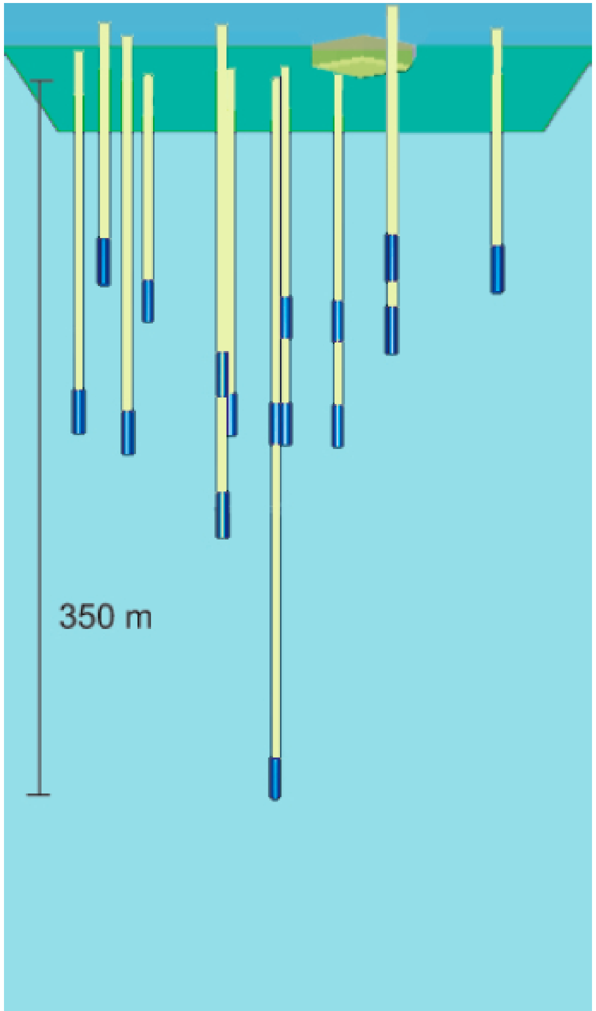
Vpol:1 neutrino candidate;

HPol:352>5 1019 eV

http://arxiv.org/abs/1003.2961

RICE experiment architecture

- Antarctic ice is neutrino target
- In-ice array of radio antennas
- 20 channels, 200-500 MHz
- Depths 100-300 meters
- Signal digitized at the surface
- Deployed near South Pole Station



10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

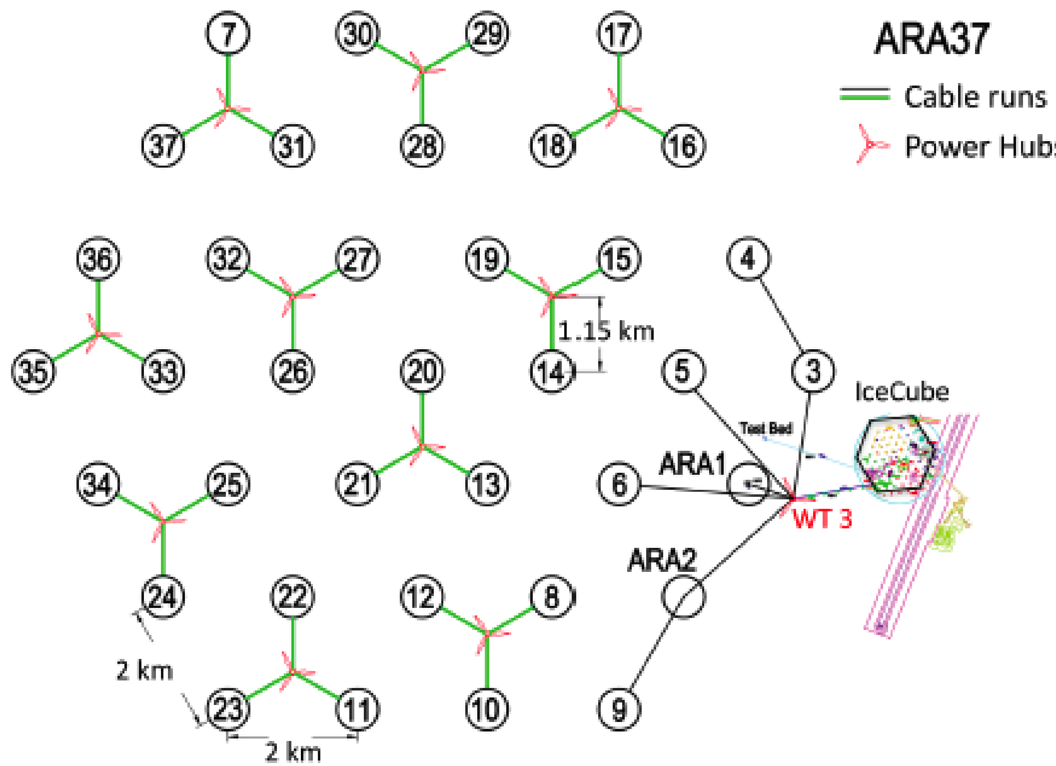
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

Scientific Goal:

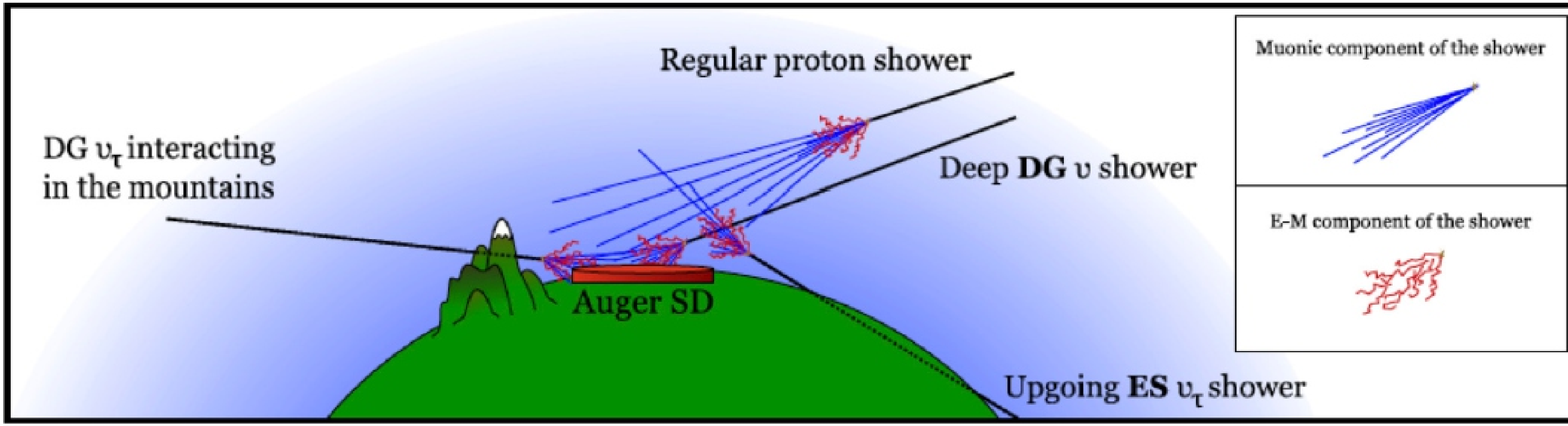
- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole



Areal coverage: ~150km^2


Regular proton shower
DG υ_τ interacting
in the mountains
Deep **DG** υ shower
Auger SD
Upgoing **ES** υ_τ shower
Muonic component of the shower
E-M component of the shower

Motivations for High Energy Neutrino Astronomy

1. Separating the "Hadronic" and "Leptonic" mechanism for gamma ray emission.

   Study of the separate populations of Electrons (positrons) and protons/nuclei in astrophysical sources.

   [Here the competition are multi-wavelength studies (synchrotron versus Inverse Compton)

2. Study of "absorbed sources" where the gamma rays cannot reach us.
   (Extragalactic sources $E > 1$ TeV)
   (GZK neutrinos)